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Technical Report
on
Interpretation of the Electrocardiogram (ECG)
Signal using Formal Methods

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Abstract

Today an evidence-based medicine has given number of medical practice clinical guidelines and protocols. Clinical guidelines systematically assist practitioners with providing appropriate health care for specific clinical circumstances. However, a significant number of guidelines and protocols are lacking in quality. Indeed, ambiguity and incompleteness are more likely anomalies in medical practices. From last few years, many researchers have tried to address the problem of protocol improvement in clinical guidelines, but results are not sufficient since they believe on informal processes and notations. Our objective is to find anomalies and to improve the quality of medical protocols using well known formal techniques, such as EVENT B. In this report, we use the EVENT B modeling language to capture guidelines for their validation. We have established a classification of possible properties to be verified in a guideline. Our approach is illustrated with a guideline which published by the National Guideline Clearing House (NGC) and AHA/ACC Society. Our main contribution is to evaluate real-life medical protocols using refinement based formal method like EVENT B for improving quality of the protocols. Refinement based formalisation is very easy to handle any complex medical protocols. For this evaluation we have selected a real-life reference protocol (ECG Interpretation) which covers a wide variety of protocol characteristics related to the several heart diseases. We formalise the given reference protocol, verify a set of interesting properties of the protocol and finally determine anomalies. Our main results are: to formalise an ECG interpretation protocol for diagnosing the ECG signal in optimal way; to discover an hierarchical structure for the ECG interpretation efficiently using incremental refinement approach; a set of properties which should be satisfied by medical protocol; verification proofs for the protocol and properties according to the medical experts; and perspectives of the potentials of this approach. Finally, we have shown the feasibility of our approach for analysing medical protocols.

Keywords: Electrocardiogram (ECG), Heart, Medical protocol, Abstract model, EVENT B, Event-driven approach, Proof-based development, Refinement.

1. Introduction

A promising and challenging application area for the application of formal methods is a clinical decision making, as it is vital that the clinical decisions are sound. In fact, ensuring safety is the primary preoccupation of medical regulatory agencies. Medical guidelines are “systematically developed statements to assist practitioners and patient decisions about appropriate health care for

specific circumstances” [1, 2]. Based on updated empirical evidence, the medical protocols provide clinicians with health-care testimonial and facilitate the spreading of high-standard practices. In fact, this way represents that adherence to protocols may reduce the costs of care upto 25% [2]. In order to reach their potential benefits, protocols must fulfill strong quality requirements. Medical bodies worldwide have made efforts in this direction, e.g. elaborating appraisal documents that take into account a variety of aspects, of both protocols and their development process. However, these initiatives are not sufficient since they rely on informal methods and notations. Informal methods and notations have not any mathematical foundations.

We are concerned with a different approach, namely the quality improvement of medical protocols through formal methods. In this report we have given on our experiences in the formalisation and verification of a medical protocol for diagnosis of the Electrocardiogram (ECG). ECG signals are too complex for diagnosis. All kinds of diseases related to the heart are predictable using 12-lead ECG signals. A high number of medical guidelines for the ECG interpretation have been published in the literature and on internet, making them more accessible. Currently, protocols are described using a combination of different formats, e.g. text, flow diagrams and tables. These approaches are used in form of informal processes and notations for analysing the medical protocols, which are not sufficient for medical practices. As a result, the ECG interpretation guidelines and protocols¹ still contain ambiguous, incomplete or even inconsistent elements.

The idea of our work is translating informal descriptions of the ECG interpretation into a more formal language, with the aim of analysing a set of properties of the ECG protocol. In addition to the advantages of such kind of formal verification, making these descriptions more formal can serve to expose problematic parts in the protocols.

Formal methods have well structure representation language with clear and well-defined semantics, which can be used for taxonomy verification of clinical guidelines and medical protocols. The representation language represents guidelines and protocols explicitly and in a non-ambiguous way. The process of verification using formal semantic representation of guidelines and protocols allow the determination of consistency and correctness.

Formal modelling and verification of medical protocols have been carried out as a case study to assess the feasibility of this approach. Throughout our case study, we have shown formal specification and verification of medical protocols. The ECG interpretation protocol is very complex, ambiguous, incomplete and inconsistent. For modeling the ECG interpretation, we consider five basic objectives as follows:

- To establish a unified theory and proper guidelines for analysing the

¹Guideline and protocol are different terms. The term protocol is used to represent a specialised version of a guideline. In this report we use them indistinctively.

ECG.

- To find ambiguity, incompleteness and inconsistency in the ECG protocol.
- Requirements and metrics for certifiable assurance and safety.
- To build a comprehensive and integrated suite of tools for the ECG interpretation supporting prediction for heart diseases.
- Refinement-based formal development to achieve less error-prone models, easier specification for the ECG interpretation protocol and reuse of such specification for further diagnosis.

The contribution of our report is to give a complete idea of the formal development of ECG interpretation protocol and we have discovered a hierarchical structure for the ECG interpretation efficiently using incremental refinement approach. Same approach can be also applied for developing a formal model of protocol of any other disease. Our approach is based on the EVENT B [3, 4] modeling language which is supported by the RODIN platform integrating tools for proving models and refinements of models. Here we present an incremental proof-based development to model and verify such interdisciplinary requirements in EVENT B [3, 4]. The ECG interpretation models must be validated to ensure that they meet requirements of the ECG protocols. Hence, validation must be carried out by both formal modeling and medical domain experts.

We have used the general formal modeling tool like Event-B [4] for modeling a complex medical protocol related to diagnoses of ECG signal. To apply a refinement based technique to model a medical protocol is our main objective. Event-B supports refinement technique. The refinement supported by the RODIN [5] platform guarantees the preservation of safety properties. The safety properties are detection of actual disease under certain conditions. The behavior of the final system is preserved by an abstract model as well as in the correctly refined models. Proof-based development methods [4] integrate formal proof techniques in the development of software systems. The main idea is to start with a very abstract model of the (closed) target system under development. Details are gradually added to this first model by building a sequence of more concrete events. The relationship between two successive models in this sequence is *refinement* [4, 6]. This technique is used to model a medical protocol more rigorously based on formal mathematics, which helps to find the anomalies and provide the consistency and correctness of the medical protocol. The current work intends to explore those problems related to the modeling of the ECG protocols. The formalization of the ECG protocol is based on original protocol and all safety properties and related assumptions are verified with the medical experts. Moreover, an incremental development of the ECG interpretation protocol model helps to discover the ambiguous, incomplete or even inconsistent elements in current the ECG interpretation protocol.

The outline of the remaining report is as follows. Section 2 contains related work. The modeling framework is presented in Section 3. Section 4 presents

selection of medical protocol for formalisation. We give a brief outline of the ECG in Section 5. In Section 6, we explore the incremental proof-based formal development of the ECG interpretation protocol. The verification results are analyzed by statistical proof and lessons learned in Section 7. Finally, in Section 8, we conclude the report and discuss future challenges.

2. Related Work

Section 2 currently presents ongoing research work related to computer-based medical guidelines and protocols for clinical purposes. From past few years many languages have been developed for representing medical guidelines and protocols using various levels of formality based on experts requirements. Although we have used EVENT B modeling language for guidelines and protocol representation in our case study. Various kinds of protocol representation languages like Asbru [7, 2], EON [8], PROforma [9] and others [10, 11] are used to represent a formal semantics of guidelines and medical protocols.

Clinical guidelines are useful tools to provide some standardization and helps for improving the protocols. A survey paper [12] presents benefits and comparison through an analysis of different kinds of systems, which are used by clinical guidelines. This paper cover a wide scope of clinical guideline related literatures and tools, which are collected from the medical informatics area.

A approach for improving guidelines and protocols is by evaluating the physician. Evaluation process involves scenario and evidence based testing which compares the actions. The actions are performed by physicians to handle particular patient case using testimonials that are prescribed by the guidelines [13]. When results of the actions deviate, evaluation process can either focused on the explanation or alternatively provide some valuable feedback for improving guidelines and protocols [14]. An intentions based evaluation process are deduced by the physicians from both the patient data and the performed actions. These are then verified against the intentions reported in the guideline.

Automated quality assessment of clinical actions and patient outcomes is another area of related work, which is used to derive structured quality indicators from formal specifications of guidelines. This technique is used in decision support [15]. Such kinds of indicators is used as formal properties in our work that guideline must comply with.

Decision-table based techniques for the verification and simplification of guidelines are presented by Shiffman et al. [16, 17]. Basic idea behind this approach is to describe guidelines as condition/action statements: *If the antecedent circumstances exist, then one should perform the recommended actions* [17]. Completeness and consistency are two main properties for verification, when guidelines and protocols are expressed in terms of decision-table. Again, these properties are internal coherence properties, whereas we are focused on domain specific properties.

Formal development of the guidelines and protocols using clinical logic may be incomplete or inconsistent. This problem is tackle by Miller et al. [18]. *If “if-then” rules are used as representation language for guidelines, incompleteness*

means that there are combinations of clinically meaningful conditions to which the system (guideline) is not able to respond [18]. The verification of rule-based clinical guidelines using semantic constraints is supported by the commander tool. This tool is able to identify clinical conditions where the rules are incomplete. Miller et al. [18] were able to find a number of missing rules in various case studies of guidelines and protocols.

Guidelines enhancement is represented through adoption of an advanced Artificial Intelligence techniques [19]. The paper has proposed an approach for verification of the guideline, which is based on the integration of a computerized guidelines management system with a model-checker. They have used SPIN model checker [20, 21] for executing and verifying medical protocols or guidelines. A framework for authoring and verification of clinical guidelines is provided by Beatriz et al [22]. The verification process of guideline is based on combined approach of Model Driven Development (MDD) and Model Checking [21] to verify guidelines against semantic errors and inconsistencies. UML [23, 24] tool is used for modeling the guidelines and a generated formal model is used as the input model for a model checker.

Jonathan et. al[25] have proposed a way to apply formal methods, namely interactive verification to improve the quality of medical protocols or guidelines. They have applied this technique for the management of jaundice in newborns based on guidelines of American Academy of Pediatrics. This paper includes formalisation of the jaundice protocol and verify some interesting properties. Simon et. al [26] have used the same protocol for improvement purpose using a modeling language Asbru, temporal logic for expressing the quality requirements, and model checking for proof and error detection.

Applying formal approach for improving medical protocol is one major area of research, which helps to the medical practitioners for improve the quality of patient care. A project Protocure [27] is an European project, which is carried out by five different institutions. Main objective of this project is for improving medical protocol through integration of formal methods. Main motivation of this project to identify anomalies like ambiguity and incompleteness in medical guidelines and protocols. Presently all medical protocols and guidelines are in text, flow diagrams and tables formats, which are easily understandable by my medical practitioners. But these are incomplete and ambiguous due to lack of formal semantics. The idea of using formal methods is to uncover these ambiguous, incomplete or even inconsistent parts of the protocols, by defining all the different descriptions more precisely using a formal language and to enable verification. Mainly the researchers have used Asbru [2] language for protocol description and KIV for interactive verification system [28].

Asbru [2] is a main modeling language for describing medical protocol and formal proof of the medical protocol is possible through KIV interactive theorem prover [28]. Guideline Markup Tool(GMT) [29] is an editor that helps translating guidelines into Asbru. An additional functionality of the tool is to define relations between the original protocol and its Asbru translation with a link macro [29]. Asbru language is used for protocol description and Asbru formalizations are translated into KIV. Asbru is considered as a semi-formal

language to support the tasks necessary for protocol-based care. It is called a semi-formal language because its semantics, although more precise than in other protocol representation languages, are not defined in a formal way. This semi-formal quality makes Asbru suitable for an initial analysis but not for systematic verification of protocols [30].

According to our literatures survey, none of the medical protocol tool exists, which is based on purely formal semantics. In this study, we have tried to model a medical protocol, completely based on formal semantics and to check various anomalies. To overcome from the existing problems [31, 30] in area of development of medical protocols, we have used the general formal modeling tool like Event-B [4] for modeling a complex medical protocol related to diagnoses of ECG signal. The main objective to use Event-B modeling language is to model medical protocol using refinement approach. Medical protocols are very complex and to model a complex protocol, a refinement approach is very helpful, which introduced peculiarity of the protocols in an incremental way. This technique is used to model a medical protocol more rigorously based on formal mathematics, which helps to find the anomalies and provide the consistency and correctness of the medical protocol.

3. The Event B modeling framework

This section presents overview of EVENT B modeling language for understanding the developed formal specification of the ECG interpretation protocol. We have used EVENT B in this development, while a model developer can use any modeling tool like Z, VDM and ASM etcetera for specifying a medical protocol. These modeling tools help to find anomalies in medical protocol, and to check the consistency and correctness of the medical protocol. For developing a medical protocol using such kinds of modeling tools, a modeler has required a good understanding of logic.

We summarize the concepts of the EVENT B modeling language developed by Abrial [3, 4] and indicate the links with the tool called RODIN [5]. The modeling process deals with various languages, as seen by considering the triptych of Bjoerner [32, 33]: $\mathcal{D}, \mathcal{S} \longrightarrow \mathcal{R}$. Here, the domain \mathcal{D} deals with properties, axioms, sets, constants, functions, relations, and theories. The system model \mathcal{S} expresses a model or a refinement-based chain of models of the system. Finally, \mathcal{R} expresses requirements for the system to be designed. Considering the EVENT B modeling language, we notice that the language can express *safety* properties, which are either *invariants* or *theorems* in a machine corresponding to the system. Recall that two main structures are available in EVENT B :

- Contexts express static information about the model.
- Machines express dynamic information about the model, invariants, safety properties, and events.

A EVENT B model is defined either as a context or as a machine. The triptych of Bjoerner [32, 33] $\mathcal{D}, \mathcal{S} \longrightarrow \mathcal{R}$ is translated as follows: $\mathcal{C}, \mathcal{M} \longrightarrow \mathcal{R}$,

where \mathcal{C} is a context, \mathcal{M} is a machine and \mathcal{R} are the requirements. The relation \longrightarrow is defined to be a logical satisfaction relation with respect to an underlying logico-mathematical theory. The satisfaction relation is supported by the RODIN platform. A machine is organizing events modifying state variables and it uses static informations defined in a context. These basic structure mechanisms are extended by the refinement mechanism which provides a mechanism for relating an abstract model and a concrete model by adding new events or by adding new variables. This mechanism allows us to develop gradually EVENT B models and to validate each decision step using the proof tool. The refinement relationship should be expressed as follows: a model M is refined by a model P , when P is simulating M . The final concrete model is close to the behavior of real system that is executing events using real source code. We give details now on the definition of events, refinement and guidelines for developing complex system models.

3.1. Modeling actions over states

The event-driven approach [3, 4] is based on the B notation. It extends the methodological scope of basic concepts to take into account the idea of *formal models*. Briefly, a formal model is characterized by a (finite) list x of *state variables* possibly modified by a (finite) list of *events*, where an invariant $I(x)$ states properties that must always be satisfied by the variables x and *maintained* by the activation of the events. In the following, we summarize definitions and principles of formal models and explain how they can be managed by tools [34, 35, 5].

Generalized substitutions are borrowed from the B notation. They provide a means to express changes to state variable values. In its simple form $x := E(x)$, a generalized substitution looks like an assignment statement. In this construct, x denotes a vector built on the set of state variables of the model, and $E(x)$ denotes a vector of expressions. Here, however, the interpretation we shall give to this statement is not that of an assignment statement. We interpret it as a *logical simultaneous substitution* of each variable of the vector x by the corresponding expression of the vector $E(x)$. There exists a more general normal form of this, denoted by the construct $x : |(P(x, x'))$. This should be read as *x is modified in such a way that the value of x afterwards, denoted by x' , satisfies the predicate $P(x, x')$* , where x' denotes the *new value* of the vector and x denotes its *old value*. This is clearly nondeterministic in general.

An event has two main parts, namely, a *guard*, which is a predicate built on the state variables, and an *action*, which is a generalized substitution. An event can take one of three normal forms. The first form (BEGIN $x : |(P(x, x'))$ END) shows an event that is not guarded, being therefore always enabled and semantically defined by $P(x, x')$. The second form (WHEN $G(x)$ THEN $x : |(Q(x, x'))$ END) and third form (ANY t WHERE $G(t, x)$ THEN $x : |(R(x, x', t))$ END) are guarded by a guard that states the necessary condition for these events to occur. The guard is represented by WHEN $G(x)$ in the second form, and by ANY t WHERE $G(t, x)$ (for $\exists t \cdot G(t, x)$) in the third form. We note that the third form defines a possibly nondeterministic event

where t represents a vector of distinct local variables. The *before-after* predicate $BA(x, x')$, associated with each of the three event types, describes the event as a logical predicate expressing the relationship linking the values of the state variables just before (x) and just after (x') the *execution* of event e . The second and the third forms are semantically equivalent to $G(x) \wedge Q(x, x')$ resp. $\exists t. (G(t, x) \wedge R(x, x', t))$.

Proof obligations
• (INV1) $Init(x) \Rightarrow I(x)$
• (INV2) $I(x) \wedge BA(e)(x, x') \Rightarrow I(x')$
• (FIS) $I(x) \wedge \text{grd}(e)(x) \Rightarrow \exists y. BA(e)(x, y)$

Table 1: EVENT B proof obligations

Proof obligations (INV 1 and INV 2) are produced by the RODIN tool [5] from events to state that an invariant condition $I(x)$ is preserved. Their general form follows immediately from the definition of the before-after predicate $BA(e)(x, x')$ of each event e (see Table 1). Note that it follows from the two guarded forms of the events that this obligation is trivially discharged when the guard of the event is false. Whenever this is the case, the event is said to be *disabled*. The proof obligation FIS expresses the feasibility of the event e with respect to the invariant I .

3.2. Model refinement

The refinement of a formal model allows us to enrich the model via a *step-by-step* approach and is the foundation of our correct-by-construction approach [36]. Refinement provides a way to strengthen invariants and to add details to a model. It is also used to transform an abstract model to a more concrete version by modifying the state description. This is done by extending the list of state variables (possibly suppressing some of them), by refining each abstract event to a corresponding concrete version, and by adding new events. The abstract (x) and concrete (y) state variables are linked by means of a *gluing invariant* $J(x, y)$. A number of proof obligations ensure that (1) each abstract event is correctly refined by its corresponding concrete version, (2) each new event refines *skip*, (3) no new event takes control for ever, and (4) relative deadlock freedom is preserved. Details of the formulation of these proofs follows.

We suppose that an abstract model AM with variables x and invariant $I(x)$ is refined by a concrete model CM with variables y and gluing invariant $J(x, y)$. If $BA(e)(x, x')$ and $BA(f)(y, y')$ are respectively the abstract and concrete before-after predicates of the same event, e and f respectively, we have to prove the following statement, corresponding to proof obligation (1):

$$I(x) \wedge J(x, y) \wedge BA(f)(y, y') \Rightarrow \exists x'. (BA(e)(x, x') \wedge J(x', y'))$$

Now, proof obligation (2) states that $BA(f)(y, y')$ must refine *skip* ($x' = x$), generating the following simple statement to prove (2).

$$I(x) \wedge J(x, y) \wedge BA(f)(y, y') \Rightarrow J(x, y')$$

In refining a model, an existing event can be refined by strengthening the guard and/or the before-after predicate (effectively reducing the degree of non-determinism), or a new event can be added to refine the *skip* event. The feasibility condition is crucial to avoiding possible states that have no successor, such as division by zero. Furthermore, this refinement guarantees that the set of traces of the refined model contains (up to stuttering) the traces of the resulting model. The refinement of an event e by an event f means that the event f simulates the event e .

The EVENT B modeling language is supported by the RODIN platform [5] and has been introduced in publications [4, 3], where there are many case studies and discussions about the language itself and the foundations of the EVENT B approach. The language of *generalized substitutions* is very rich, enabling the expression of any relation between states in a set-theoretical context. The expressive power of the language leads to a requirement for help in writing relational specifications, which is why we should provide guidelines for assisting the development of EVENT B models.

4. Selection of medical protocol

Concerning the protocols that are the object of our study, we have selected the ECG interpretation that cover a wide range of protocol characteristics related to the heart diseases. All kinds of medical guidelines and protocols differ from each others along several dimensions, which can be refer to the contents of the protocols or to its form. General practitioners (GPs), nurses and a large group of people related to this domain² are the *most important target users* of guidelines and protocols, and main aspects of clinical practice is to cover *diagnosis* as well as helps in treatments. Medical guidelines and protocols, which are used by general practitioners and nurses, are also characterized by time dimensions; short time-span protocols; long-time span protocols. The form of guidelines and protocols are related to textual descriptions. Sometimes it is also represented textual form as well as combination with *tables* and *flowcharts*.

The ECG interpretation protocol [37, 38] aims at cardiologist as well as GPs and covers both diagnosis and treatment over a long period of time. The ECG interpretation protocol can be considered more precisely: one is in daily use by cardiologist and the other is included in the repository of the National Guideline Clearinghouse(NGC), American College of Cardiology/American Heart Association (ACC/AHA). Basic standard for inclusion in the NGC and ACC/AHA are that guidelines and protocols contain well structured meaningful informations and systematically developed statements. The contents are produced under the supervision of medical specialty associations. It should be also based on literatures, reviewed and revised within the last 5 years. Furthermore, the ECG

²<http://www.guideline.gov/>

interpretation protocol has been published in a peer-reviewed scientific journal. In summary, the chosen protocol covers different aspects while fulfilling high quality standards, which are good criteria for selection of our case study.

In the following sections we will use the ECG interpretation protocol as the main example in our explanations, and we therefore give a brief description of this protocol. Electrocardiogram (ECG or EKG) interpretation is a common technique to trace abnormalities in the heart system and various levels of tracing help to find severe diseases. The guideline is more than 100 pages document, which contains knowledge in various notations: the main text; a list of factors to be considered when assessing an abnormality in heart ECG signal and a flowchart describing the steps in the ECG interpretation protocol. The protocol consists of an evaluation (or diagnosis) part and a treatment part, to be performed in successive way. During the application of guidelines and protocols, as soon as the possibility of a more serious disease is uncovered, the recommendation is to leave the protocol without any further action.

5. Basic overview of Electrocardiogram (ECG)

The electrocardiogram (ECG or EKG) [37, 39] is a diagnostic tool that measures and records the electrical activity of the heart precisely in form of signals. Clinicians can evaluate the conditions of a patient's heart from the ECG and perform further diagnosis. Analysis of these signals can be used for interpreting diagnosis of a wide range of heart conditions and predict related diseases. ECG records are obtained by sampling the bioelectric currents sensed by several electrodes, known as leads. A typical one-cycle ECG tracing is shown in Fig.-1. Electrocardiogram term is introduced by Willem Einthoven in 1893 at a meeting of the Dutch Medical Society. In 1924, Einthoven received the Nobel Prize for his life's work in developing the ECG [37, 40, 41, 38, 42, 43, 39, 44].

The normal electrocardiogram (ECG or EKG) is depicted in Fig.-1. All kinds of segments and intervals are represented in this ECG diagram. Depolarization and repolarization of ventricular and atrial chambers are presented by deflection of the ECG signal. All these deflections are denoted by alphabetic order (P-QRS-T). Letter P indicates atrial depolarization and the ventricular depolarization is represented by QRS complex. The ventricular repolarization is represented by T-wave. Atrial repolarization appears during the QRS complex and generates very low amplitude signal which cannot be uncovered from the normal ECG signal.

5.1. Differentiating the P-, QRS- and T-waves

Sequential activation, depolarization, and repolarization are deflected distinctly in ECG due to anatomical difference of the atria and the ventricles. Even all sequences are easily distinguishable when they are not in correct sequence: P-QRS-T. QRS-complex are easily identifiable between P- and T-wave because it has characteristic waveform and dominating amplitude. This amplitude is about 1000 μm in a normal heart and can be much greater in ventricular

hypertrophy. Normal duration of the QRS-complex is 80-90 ms. In case of non-existence of atrial hypertrophy, an amplitude and duration of P-wave is about 100 μm and 100 ms, respectively. The T-wave has about twice of the amplitude and duration of the P-wave. The T-wave can be differentiated from the P-wave by observing that the T-wave follows the QRS-complex after about 200 ms. In ECG signal several parameters are used to evaluate the conditions of a patient's heart from the ECG. The parameters are: PR-interval, P-wave, QRS duration, Q-wave, R-wave, ST-segment, T-wave, Axis, QT-interval. All these parameters have several different characteristics that are used for diagnosis.

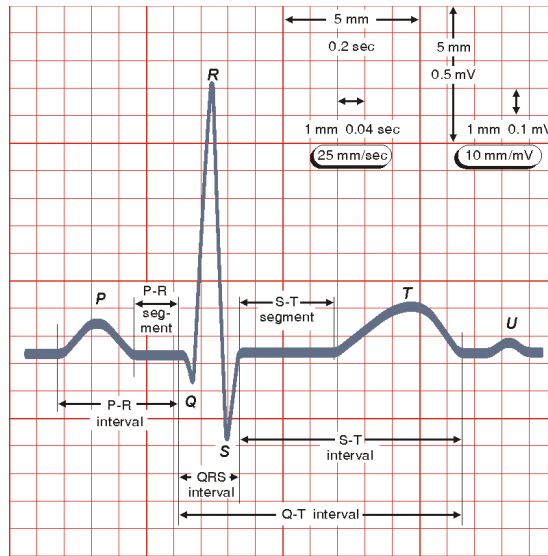


Figure 1: A typical one-cycle ECG tracing [44]

6. Formal development of the ECG interpretation

6.1. Abstract model : Assessing rhythm and rate

We begin by defining the EVENT B context. The context uses sets and constants to define axioms and theorems. Axioms and theorems represent the logical theory of the system. The logical theory is the static properties and properties of the target system. In the context, we define constants *LEADS*, *HState* and *YesNoState* that are related to the enumerated set of ECG leads, normal and abnormal states of the heart and yes-no states, respectively. These constants are extracted from the ECG interpretation protocol [37, 41, 43, 39]. The standard 12-lead electrocardiogram is a representation of the heart's electrical activity recorded from electrodes on the body surface. The set of leads is represented as $LEADS = \{I, II, III, aVR, aVL, aVF, V1, V2, V3, V4, V5, V6\}$. Normal and abnormal states of heart are represented by $HState = \{OK, KO\}$ and yes-no

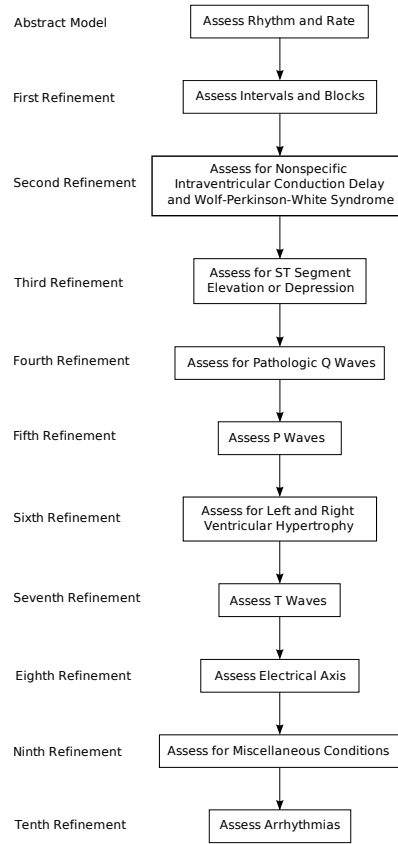


Figure 2: ECG interpretation protocols refinements

states are represented by $YesNoState = \{Yes, No\}$. Fig.-2 represents a view of incremental formal development of the ECG interpretation protocol. In our development process some refinements are decomposed into several refinements for the simplicity. Every refinement level introduces a *diagnosis* criteria for different components of the ECG signal and each new criteria helps to analyse particular a set of diseases. Particular set of diseases is introduced in multiple context related to each refinement.

Figure 3 shows an abstract representation of a *diagnostic-based* system development. Root circle (?) represents set of conditions for testing any particular disease abstractly. The possible abstract outcomes of diagnosis criteria are in form of *OK* and *KO*, which are represented by two branches. *KO* represents that diagnosis criteria has found some conditions for further testing, while *OK* represents absence of any disease. Dash line of circles and arrows represent next level of refinement for further analysing any particular diseases according to guidelines and protocols.

Our abstract EVENT B model of the ECG interpretation protocol assess

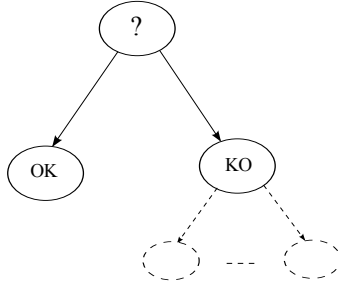


Figure 3: Abstract Representation

rhythm and *heart rate* to distinguish normal and abnormal heart. The specification consists of just three state variables ($inv1 - inv3$) *Sinus*, *Heart_Rate* and *Heart_State*. *Sinus* variable is represented by *YesNoState* as an enumerated sets. Last two variables *Heart_Rate* and *Heart_State* are introduced as to show heart rate limit and heart states. One possible approach is to introduce a set of variables ($RR_Int_equidistant$, $PP_Int_equidistant$, $P_Positive$, $PP_Interval$ and $RR_Interval$) representing total functions mapping leads (LEADS) to an standard data type ($BOOL, \mathbb{N}$) in invariants ($inv4 - inv8$). The RR and PP equidistant intervals in the ECG signal are represented by variables $RR_Int_equidistant$ and $PP_Int_equidistant$ as the total functions from *LEADS* to *BOOL*. $RR_Int_equidistant$ and $PP_Int_equidistant$ are functions which represent RR and PP equidistant intervals states in boolean form. A variable $P_Positive$ represents positive wave of the signal also as a total function from *LEADS* to *BOOL*. The $P_Positive$ function is used to show the positive visualization of the P-waves. The next variables PP and RR intervals in the ECG signal are represented by the variables $PP_Interval$ and $RR_Interval$ as total functions from *LEADS* to \mathbb{N} . $PP_Interval$ and $RR_Interval$ functions are used to calculate PP and RR-intervals.

```

inv1 : Sinus ∈ YesNoState
inv2 : Heart_Rate ∈ 1..300
inv3 : Heart_State ∈ HState
inv4 : RR_Int_equidistant ∈ LEADS → BOOL
inv5 : PP_Int_equidistant ∈ LEADS → BOOL
inv6 : P_Positive ∈ LEADS → BOOL
inv7 : PP_Interval ∈ LEADS → ℕ
inv8 : RR_Interval ∈ LEADS → ℕ
inv9 : P_Positive(II) = FALSE ⇒ Sinus = No
inv10 : ((∀l·l ∈ {II, V1, V2} ⇒
  PP_Int_equidistant(l) = FALSE ∨
  RR_Int_equidistant(l) = FALSE ∨
  RR_Interval(l) ≠ PP_Interval(l))
  ∨
  P_Positive(II) = FALSE) ⇒ Sinus = No
inv11 : Sinus = Yes ⇒ ((∃l·l ∈ {II, V1, V2} ∧
  PP_Int_equidistant(l) = TRUE ∧
  RR_Int_equidistant(l) = TRUE ∧
  RR_Interval(l) = PP_Interval(l))
  ∧
  P_Positive(II) = TRUE)
inv12 : Heart_Rate ∈ 60..100 ∧ Sinus = Yes ⇒
  Heart_State = OK
inv13 : Heart_Rate ∈ 1..300 \ 60..100 ∧ Sinus = Yes
  ⇒ Heart_State = KO
inv14 : Heart_Rate ∈ 60..100 ∧ Sinus = No ⇒
  Heart_State = KO

```

All invariants (*inv9*–*inv14*) represent safety properties and these are used to verify required conditions for the ECG interpretation protocol using all possible behavior of the heart system and analysis of signal features which are collected from the ECG signals. All these safety properties are designed under the supervision of cardiologist experts to verify the correctness of the formal model. These invariants in form of safety properties are extracted from the original protocol.

The invariant (*inv9*) states that if positive visualization of P-wave is *FALSE*, then there is no sinus rhythm. According to the clinical document, lead II is best for visualization of P-waves to determine the presence of sinus rhythm. Next invariant (*inv10*) is more stronger invariant to identify non existence of sinus rhythm. This invariant states that if PP intervals (*PP_Int_equidistant*) or RR intervals (*RR_Int_equidistant*) are not equidistant (*FALSE*), or RR intervals (*RR_Interval*) and PP intervals (*PP_Interval*) are not equivalent, in all leads (II,V1,V2), or positive visualization of P-wave in lead II is *FALSE*, then there is no sinus rhythm. Similarly, next invariant (*inv11*) confirms, if the rhythm is sinus, then the PP intervals (*PP_Int_equidistant*) and RR intervals (*RR_Int_equidistant*) are equidistant, and RR intervals (*RR_Interval*) and PP intervals (*PP_Interval*) are equal, exist in any leads (II,V1,V2), and the P-wave is positive in lead II. The invariant (*inv12*) represents that if heart rate (*Heart_Rate*) is belonging between 60-100 bpm and sinus rhythm is *Yes*, then *Heart_State* is *OK*. Next two invariants (*inv13* – *inv14*) represent *KO* state of Heart, mean heart has any disease. The invariant (*inv13*) states that if heart rate (*Heart_Rate*) is belonging between less than 60 bpm and greater than 100 bpm but less then 300 bpm, and sinus rhythm is *Yes*, then heart state (*Heart_State*) is *KO*. Similarly, in last invariant (*inv14*) represents that

if heart rate (*Heart_Rate*) is in between 60-100 bpm and sinus rhythm is *No*, then *Heart_State* is *KO*, means heart has any disease.

Three significant events *Rhythm_test_TRUE*, *Rhythm_test_FALSE* and *Rhythm_test_TRUE_abRate* are introduced in the abstract model. The *Rhythm_test_TRUE* represents successful ECG testing and found sinus rhythm *Yes* and heart state is *OK*. The next event *Rhythm_test_FALSE* represents successful ECG testing and found sinus rhythm is *No* and heart state is *KO*. Third event *Rhythm_test_TRUE_abRate* represents successful ECG testing and found sinus rhythm is *Yes* and heart state is *KO* due to abnormal heart rate. These events are the abstract events, which are equivalent to the first step of diagnosis of the ECG signal of the original protocol. We have taken some assumptions for modeling the medical protocol. These assumptions are extracted from the original protocol. In our formal model all invariants and assumptions are verified with the medical experts. Our developed formal are always compile with existing original protocols.

Mostly events are used to test criteria of possible disease using ECG features. The criteria for testing sinus rhythm is to focus on leads V1, V2, and II. Leads V1 and II are best for visualization of P-waves to determine the presence of sinus rhythm or an arrhythmia, and V1 and V2 are best to observe for bundle branch block. If P-waves are not clearly visible in V1, assess them in lead II, which usually shows well-formed P-waves [37]. Identification of the P-wave and then the RR intervals allows the interpreter to discover immediately whether the rhythm is sinus or other and to take the following steps:

- Confirm, if the rhythm is sinus, that the RR intervals are equidistant, that the P-wave is positive in lead II, and that the PP intervals are equidistant and equal to the RR interval.
- Do an arrhythmia assessment if the rhythm is abnormal.
- Determine the heart rate.

```

EVENT Rhythm_test_TRUE
ANY rate
WHEN
  grd1 : ( $\exists l.l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
     $RR\_Int\_equidistant(l) = TRUE \wedge$ 
     $RR\_Interval(l) = PP\_Interval(l) \wedge$ 
     $P\_Positive(II) = TRUE$ 
  )
  grd2 :  $rate \in 60 .. 100$ 
THEN
  act1 : Sinus := Yes
  act2 : Heart_Rate := rate
  act3 : Heart_State := OK
END

```

```

EVENT Rhythm_test_FALSE
ANY rate
WHEN
  grd1 : ( $\forall l.l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE$ 
     $\vee RR\_Int\_equidistant(l) = FALSE \vee$ 
     $RR\_Interval(l) \neq PP\_Interval(l) \vee$ 
     $P\_Positive(II) = FALSE$ )
  grd2 : rate  $\in 1..300$ 
THEN
  act1 : Sinus := No
  act2 : Heart_Rate := rate
  act3 : Heart_State := KO
END

```

```

EVENT Rhythm_test_TRUE_abRate
ANY rate
WHEN
  grd1 : ( $\exists l.l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
     $RR\_Int\_equidistant(l) = TRUE \wedge$ 
     $RR\_Interval(l) = PP\_Interval(l) \wedge$ 
     $P\_Positive(II) = TRUE$ )
  grd2 : rate  $\in 1..300 \setminus 60..100$ 
THEN
  act1 : Sinus := Yes
  act2 : Heart_Rate := rate
  act3 : Heart_State := KO
END

```

In the abstract model, we have seen that sinus rhythm and heart rate are introduced for the ECG interpretation in a single atomic step. This provides for a clear and simple specification of the essence of the basic ECG interpretation protocol and predicts the heart state (*OK* or *KO*). However, in the real protocol, the ECG interpretation and heart state prediction is not atomic. Instead, the ECG interpretation and prediction are also encounter lots of diagnosis to find the various kinds of heart diseases.

6.2. Overview of the Full Refinement Chain

So far we have described our abstract model of the ECG interpretation protocol. Every level of refinement introduces new context file for adding static properties of the system and list of heart diseases after introducing certain protocol of the ECG interpretation. Every refinement level is used to introduce new set of diagnosis criteria to test the ECG signals. Rather than presenting the other chain of refinement stages in similar detail (see in section 6.1), we will just present a sufficient overview of the remaining refinement stages helping the reader to understand the rational of each refinement stage for formalising the ECG interpretation protocol.

6.2.1. First Refinement : Assess intervals and blocks

In an abnormal ECG signal, all ECG features are varying according to symptoms of the heart diseases. We will formalise the ECG interpretation protocol using incremental approach, where we determine all features of the ECG signal. This level of refinement determines the PR- and QRS-intervals for the ECG interpretation. These intervals classify different kinds of heart disease.

Invariants (*inv1* – *inv3*) represent a set of new introduced variables in the refinement for expressing formalisation of the ECG interpretation protocol. These variables are *PR_Int*, *Disease_step2*, *QRS_Int*. Other variables (*M_Shape_Complex*, *Slurred_S*, *Notched_R*, *Small_R_QS* and *Slurred_S_duration*) are introduced as total functions in invariants (*inv4* – *inv8*) where total functions are mapping from leads (LEADS) to *BOOL* and \mathbb{N}_1 , respectively. Function *M_Shape_Complex* returns existence of M-shape complex from the ECG signals in form of *TRUE* and *FALSE*. The function *Slurred_S* represents Slurred S-wave, the function *Notched_R* represents notched R-wave and the function *Small_R_QS* represents small R or QS waves, in boolean form. The function *Slurred_S_duration* is used to calculate slurred S duration. A set of invariants (*inv9* – *inv14*) represent safety properties to validate formal representation of the ECG interpretation protocol. All these properties are derived from the original protocol to verify the correctness and consistency of the system. These properties are formulated through logic experts as well as cardiologist experts according to the original protocols. The main advantage of this technique is that if any property is not holding by the model, then it helps to find anomalies or to find missing parts of the model such as required conditions and parameters.

Invariants (*inv9* – *inv13*) represent an abnormal state of heart (*KO*) due to finding any disease and unsatisfiable condition for features of the ECG signal, in formal diagnosis process. While the last invariant (*inv14*) represents all required properties for a normal heart. It states that if heart rate is in between 60 to 100 bpm, sinus rhythm is *Yes*, PR interval is less than or equal to 200 ms and QRS interval is less than 120 ms, then the heart state is *OK*.

```

inv1 : PR_Int ∈ 120 .. 250
inv2 : Disease_step2 ∈ Disease_Codes_Step2
inv3 : QRS_Int ∈ 50 .. 150
inv4 : M_Shape_Complex ∈ LEADS → BOOL
inv5 : Slurred_S ∈ LEADS → BOOL
inv6 : Notched_R ∈ LEADS → BOOL
inv7 : Small_R_QS ∈ LEADS → BOOL
inv8 : Slurred_S_duration ∈ LEADS → ℕ1
inv9 : Sinus = Yes ∧ PR_Int > 200 ∧ Disease_step2 =
      First_degree_AV_Block ⇒ Heart_State = KO
inv10 : Sinus = Yes ∧ QRS_Int ≥ 120 ∧
      Disease_step2 ∈ {LBBB, RBBB} ⇒ Heart_State = KO
inv11 : Sinus = Yes ∧ Disease_step2 = First_degree_AV_Block
      ⇒ Heart_State = KO
inv12 : Sinus = Yes ∧ Disease_step2 = LBBB ⇒
      Heart_State = KO
inv13 : Sinus = Yes ∧ Disease_step2 = RBBB ⇒
      Heart_State = KO
inv14 : Heart_Rate ∈ 60 .. 100 ∧ Sinus = Yes ∧ PR_Int ≤ 200
      ∧ QRS_Int < 120 ⇒ Heart_State = OK

```

To express formal logic for a new set of diagnoses for the ECG signal, we have introduced three events *PR_test*, *QRS_Test_LBBB* and *QRS_Test_RBBB*. The *PR_Test* intervals represent, if PR intervals are abnormal (>200 ms), consider first-degree atrioventricular (AV) block. The next two events *QRS_Test_LBBB* and *QRS_Test_RBBB* are used to assess the QRS duration for bundle branch block and states that, if QRS interval is ≥ 120 ms, bundle branch block is present.

Understanding the genesis of the QRS complex is an essential step and clarifies the ECG manifestations of bundle branch blocks [37]. We have formalised the basic criteria to distinguish between RBBB and LBBB in diagnosis process. The basic description of RBBB and LBBB are given as follows:

Right Bundle Branch Block (RBBB)

- QRS duration ≥ 120 ms.
- M-shaped complex in V1 and V2.
- Slurred S-wave in leads 1, V5, V6; and an S-wave that is of greater amplitude (length) than the preceding R-wave.

Left Bundle Branch Block (LBBB)

- QRS duration ≥ 120 ms.
- A small R- or QS-wave in V1 and V2.
- A notched R-wave in leads 1, V5, and V6.

Due to limited space, we will not show the formal representation of introduced events. For complete detail see [45].

6.2.2. Second Refinement : Assess for nonspecific intraventricular conduction delay and wolff-parkinson-white syndrome

This level of refinement of the ECG interpretation assess for nonspecific intraventricular conduction delay (IVCD) and wolff-parkinson-white (WPW) syndrome. WPW syndrome may mimic an inferior MI (see in further refinements). If WPW syndrome, RBBB, or LBBB is not present, interpret as nonspecific intraventricular conduction delay (IVCD) and assess for the presence of electronic pacing [37]. Some new variables (*Delta_Wave* and *Disease_step3*) are introduced in this refinement to assess atypical right bundle branch block using ECG signal. Two invariants (*inv3* – *inv4*) are used to declare new variables in form of the total function mapping leads (LEADS) to *BOOL*. These functions are used to calculate ST-segment elevation and epsilon wave, respectively. Invariants (*inv5* – *inv8*) represent an abnormal state of heart (*KO*) when sinus rhythm is *Yes* and any new particular disease is found in this refinement. All these properties are derived from the original protocol to verify the correctness and consistency of the system according to the cardiologist.

```

inv1 : Delta_Wave ∈ ℕ
inv2 : Disease_step3 ∈ Disease_Codes_Step3
inv3 : ST_elevation ∈ LEADS → BOOL
inv4 : Epsilon_Wave ∈ LEADS → BOOL
inv5 : Sinus = Yes ∧ Disease_step3 = WPW_Syndrome ⇒
      Heart_State = KO
inv6 : Sinus = Yes ∧ Disease_step3 = Brugada_Syndrome ⇒
      Heart_State = KO
inv7 : Sinus = Yes ∧ Disease_step3 = RV_Dysplasia ⇒
      Heart_State = KO
inv8 : Sinus = Yes ∧ Disease_step3 = IVCD ⇒
      Heart_State = KO

```

We have introduced four events *QRS_Test_Atypical_RLBBB_WPW_Syndrome*, *QRS_Test_Atypical_RBBB_Brugada_Syndrome*, *QRS_Test_Atypical_RBBB_RV-Dysplasia* and *QRS_Test_Atypical_RBBB_IVCD* to interpret atypical right bundle branch block using QRS interval. The following criteria to assess are as follows:

- If the QRS duration is prolonged ≥ 110 ms and bundle branch block appears to be present but is atypical, consider WPW syndrome, particularly if there is a tall R wave in leads V1 and V2.
- Assess for a short PR interval ≤ 120 ms and for a delta wave.

6.2.3. Third Refinement : Assess for ST-segment elevation or depression

This refinement provides the criteria for ST-segments assessment by introducing some new variables (*ST_seg_ele* and *ST_depression*) in form of total function mapping leads (LEADS) to \mathbb{N} in invariants (*inv2* – *inv3*). ST-segment for elevation and ST depression features are calculated by *ST_seg_ele* and *ST_depression* functions. Invariants (*inv4* – *inv8*) are introduced as representing the safety properties to confirm an abnormal state of heart (*KO*) when sinus rhythm is *Yes* and a new disease is found in this refinement.

```

inv1 : Disease_step4 ∈ Disease_Codes_Step4
inv2 : ST_seg_ele ∈ LEADS → ℕ
inv3 : ST_depression ∈ LEADS → ℕ
inv4 : Sinus = Yes ∧ Disease_step4 ∈
      {Acute_inferior_MI, Acute_anterior_MI}
      ⇒ Heart_State = KO
inv5 : Sinus = Yes ∧ Disease_step4 = STEMI ⇒
      Heart_State = KO
inv6 : Sinus = Yes ∧ Disease_step4 ∈ {Troponin, CK_MB} ⇒
      Heart_State = KO
inv7 : Sinus = Yes ∧ Disease_step4 = Non_STEMI ⇒
      Heart_State = KO
inv8 : Sinus = Yes ∧ Disease_step4 = Ischemia ⇒
      Heart_State = KO

```

Four new events *ST_seg_elevation_YES*, *ST_seg_elevation_NOTCKMB_Yes*, *ST_seg_elevation_NO_TCKMB_No* and *Acute_IA_MI* are defined to cover *diagnosis* related to the ECG signals. All these events are used to interpret about the ECG signal using ST-segment elevation or depression features [37]. To assess the ST-segments elevation or depression, we have formalised the following textual criteria:

- Focus on the ST-segment for elevation or depression. ST-elevation ≥ 1000 μm (0.1 mV) in two or more contiguous ECG leads in a patient with chest pain indicates ST elevation MI (STEMI). The diagnosis is strengthened if there is reciprocal depression.
- ST-elevation in leads II, III, and aVF, with marked reciprocal depression in leads I and aVL, diagnostic of acute inferior MI.

- ST-segment elevation in V1 through V5, caused by extensive acute anterior MI.
- The ECG of a patient with a subtotal occlusion of the left main coronary artery. Note the ST elevation in aVR is greater than the ST elevation in V1, a recently identified marker of left main coronary disease.
- Features of non-ST-elevation MI (nonQ-wave MI).
- Elevation of the ST-segment may occur as a normal variant and ST-segment abnormalities and MI.

These textual sentences are formulated in incremental development of our ECG protocol. This refinement advises scrutiny of the ST-segment before assessment of T-waves, electrical axis, QT interval, and hypertrophy because the diagnosis of acute MI or ischemia is vital and depends on careful assessment of the ST-segment. Above given criteria are more complex and too ambiguous to represent. Therefore, we have formalised this part through careful cross reading of many reliable sources such as literature and encounter suggestion of the medical experts.

6.2.4. Fourth Refinement : Assess for pathologic Q-wave

This refinement only introduces new guidelines to interpret Q-wave feature of the ECG signal and assessment related diseases to the Q-wave and R-wave [37]. Some new variables are represented by set of invariants (*inv1 – inv2*) to handle the required features of Q-wave and R-wave to diagnose the ECG signal. The functions *Q_Normal_Status* and *R_Normal_Status* represent normal state of Q and R-waves in boolean form. Next three invariants (*inv3 – inv5*) are used to declare new variables in form of total function mapping leads (LEADS) to \mathbb{N} , and invariant (*inv6*) is also total function mapping leads (LEAD) to *BOOL*. The functions *Q_Width*, *Q_Depth* and *R_Depth* calculate Q-wave width, Q-wave depth and R-wave depth, respectively. The last function *Q_Wave_State* represents boolean state of Q-wave for all leads. Two other new variables *Age_of_Inf* and *Misce_State* represent infarction age and miscellaneous states. An enumerated set of infarction age and miscellaneous states define as *Age_of_Infarct* = {*recent, indeterminate, old*} and *Misce_State5* = {*Exclude_Mimics_MI, late_transition, normal_variant, borderline_Qs, NMS*}, respectively in context. The variable *Disease_step5* represents a group of diseases of this refinement level as analysis of Q-wave from the ECG signals. Invariants (*inv10 – inv13*) are introduced as representing the safety properties to confirm an abnormal state of heart (*KO*). All invariants have similar form for checking heart state under various disease conditions. These invariants state that if sinus rhythm is *Yes* and new disease is found, then the heart must be in abnormal state (*KO*).

```

inv1 : Q_Normal_Status ∈ BOOL
inv2 : R_Normal_Status ∈ BOOL
inv3 : Q_Width ∈ LEADS → ℕ
inv4 : Q_Depth ∈ LEADS → ℕ
inv5 : R_Depth ∈ LEADS → ℕ
inv6 : Q_Wave_State ∈ LEADS → BOOL
inv7 : Age_of_Inf ∈ Age_of_Infarct
inv8 : Mice_State ∈ Mice_State5
inv9 : Disease_step5 ∈ Disease_Codes_Step5
inv10 : Sinus = Yes ∧ Disease_step4 = Acute_anterior_MI ⇒
Heart_State = KO
inv11 : Sinus = Yes ∧ Disease_step4 = Acute_inferior_MI ⇒
Heart_State = KO
inv12 : Sinus = Yes ∧ Disease_step5 =
Hypertrophic_cardiomyopathy
⇒ Heart_State = KO
inv13 : Sinus = Yes ∧ Disease_step5 ∈
{anterior_MI, LVH, emphysema, lateral_MI}
⇒ Heart_State = KO

```

In this level of refinement, we have introduced nine events (*Q_Assessment_Normal*, *Q_Assessment_Abnormal_AMI*, *Q_Assessment_Abnormal_IMI*, *Determine_Age_of_Infarct*, *Exclude_Mimics*, *R_Assessment_Normal*, *R_Assessment_Abnormal*, *R_Q_Assessment_R_Abnormal_V1234* and *R_Q_Assessment_R_Abnormal_V56*) for assessing the Q-wave and R-wave in all leads of the ECG signals. We have represented the formal notation of following guidelines, which are used to assess the Q-wave and the R-wave:

- Assess for the loss of R waves-pathologic Q-waves in leads I, II, III, aVL, and aVF.
- Assess for R wave progression in V2 through V4. The variation in the normal QRS configuration that occurs with rotation. The R wave amplitude should measure from 1 mm to at least 20000 μm in V3 and V4. Loss of R waves in V1 through V4 with ST-segment elevation indicates acute anterior MI.
- Loss of R wave in leads V1 through V3 with the ST-segment isoelectric and the T-wave inverted may be interpreted as anteroseptal MI age indeterminate (i.e., infarction in the recent or distant past). Features are given of old anterior MI and lateral infarction in this refinement.

Sometimes, R-wave progression in leads V2 through V4 are very poor, may be caused by the following reasons: improper lead placement, late transition, anteroseptal or anteroapical MI, LVH Severe chronic obstructive pulmonary disease, particularly emphysemaemphysema may cause QS complexes in leads V1 through V4, which may mimic MI; a repeat ECG with recording electrodes placed one intercostal space below the routine locations should cause R waves to be observed in leads V2 through V4, Hypertrophic cardiomyopathy, LBBB [37].

6.2.5. Fifth Refinement : P-wave

This refinement level introduces a criteria to assess the P-wave for abnormalities including atrial hypertrophy into the ECG signal [37]. A new vari-

able *Disease_step6* is introduced in this refinement to introduce a set of diseases related to the P-wave. Some new variables are also introduced to assess the P-wave from 12-leads ECG signals, which are represented by *inv2* – *inv4*. First two invariants introduce new variables in form of total function mapping from leads (LEADS) to \mathbb{N} . These functions return height and broadness of P-waves. Next invariant (*inv4*) represents total function mapping leads (LEADS) to *BOOL*. It returns diphasic state in the boolean form. Invariants (*inv5* – *inv7*) are representing the confirmation of the abnormal state of heart (*KO*). These invariants state that if sinus rhythm is *Yes* and a new disease is found, then heart will be in abnormal state. In invariant (*inv5*) is checking for existence of multiple diseases during the P-wave diagnosis. Five new events *P_Wave_assessment_Peaked_Broad_No*, *P_Wave_assessment_Peaked_Yes*, *P_Wave_assessment_Peaked_Yes_Check_RAE*, *P_Wave_assessment_Broad_Yes* and *P_Wave_asses-smment_Broad_Yes_Check_LAE* are introduced to assess the P-wave.

```

inv1 : Disease_step6 ∈ Disease_Codes_Step6
inv2 : P_Wave_Peak ∈ LEADS → ℕ
inv3 : P_Wave_Broad ∈ LEADS → ℕ
inv4 : Diphasic ∈ LEADS → BOOL
inv5 : Sinus = Yes ∧ Disease_step6 ∈
      {RVH, RV_strain, pulmonary_embolism,
       RAE, mitral_stenosis, mitral_regurgitation, LV_failure,
       LAE, dilated_cardiomyopathy, LVH_cause}
      ⇒ Heart_State = KO
inv6 : Sinus = Yes ∧ Disease_step6 = LAE ⇒ Heart_State = KO
inv7 : Sinus = Yes ∧ Disease_step6 = RAE ⇒ Heart_State = KO

```

The textual representation of formal notation of the P-wave assessment is given in [37]. We have formalised all textual guidelines.

6.2.6. Sixth Refinement : Assess for left and right ventricular hypertrophy

Left Ventricular Hypertrophy (LVH) and Right Ventricular Hypertrophy (RVH) are assessed by this refinement. The criteria for LVH and RVH are not applicable if bundle branch block is present [37]. Thus, it is essential to exclude LBBB and RBBB early in the interpretive sequences as delineated previously in refinement 2 and refinement 3. This refinement introduces two new variables *S_Depth* and *R_S_Ratio* in form of total function mapping leads (LEADS) to \mathbb{N} . These functions are used to calculate S-wave depth and ratio of R-wave and S-wave from 12-leads ECG signal. Invariants (*inv3* – *inv4*) are used to verify an abnormal state (*KO*) of the heart in case of detecting any disease. Two new events (*LVH_Assessment* and *RVH_Assessment*) are introduced to assess LVH and RVH from 12-leads ECG. Detailed textual representation of assessment of LVH and RVH is given in [37].

```

inv1 : S_Depth ∈ LEADS → ℕ
inv2 : R_S_Ratio ∈ LEADS → ℕ
inv3 : Sinus = Yes ∧ Disease_step6 = RVH ⇒
      Heart_State = KO
inv4 : Sinus = Yes ∧ Disease_step6 = LVH_cause ⇒
      Heart_State = KO

```


6.2.7. Seventh Refinement : Assess T-wave

This refinement is used to assess the pattern of T-wave changes in 12-leads ECG signals. T-wave changes are usually nonspecific [37]. The T-wave inversion associated with ST-segment depression or elevation indicates myocardial ischemia. A new variable T_Normal_Status represents as a boolean state like $TRUE$ is for normal state, and $FALSE$ is for abnormal state. Variable $Disease_step8$ is introduced in this refinement to assess a set of diseases related to T-wave from the ECG signals. Invariants ($inv3 - inv8$) represent variables in form of total function mapping leads (LEADS) to possible other attributes ($T_State, T_State_B, BOOL, \mathbb{N}$ and $T_State.L.d$). The function T_Wave_State represents T-wave states like peaked or flat, or inverted. Similarly, the function $T_Wave_State_B$ also represents the T-wave states like upright or inverted, or variable using second method of diagnosis of the T-wave. The function $Abnormal_Shaped_ST$ and $Asy_T_Inversion_strain$ returns boolean state of the abnormal ST-shape and asymmetric T-wave inversion strain pattern, respectively. Function $T_inversion$ calculates deep T-wave inversion and last function $T_inversion.L.d$ represents localized and diffuse T-inversion.

```

inv1 : T_Normal_Status ∈ BOOL
inv2 : Disease_step8 ∈ Disease_Codes_Step8
inv3 : T_Wave_State ∈ LEADS → T_State
inv4 : T_Wave_State_B ∈ LEADS → T_State_B
inv5 : Abnormal_Shaped_ST ∈ LEADS → BOOL
inv6 : Asy_T_Inversion_strain ∈ LEADS → BOOL
inv7 : T_inversion ∈ LEADS → ℕ
inv8 : T_inversion.L.d ∈ LEADS → T_State.L.d
inv9 : Sinus = Yes ∧ Disease_step8 = Nonspecific ⇒
      Heart_State = KO
inv10 : Sinus = Yes ∧ Disease_step8 =
      Nonspecific_ST_T_changes
      ⇒ Heart_State = KO
inv11 : Sinus = Yes ∧ Disease_step8 = posterior_MI ⇒
      Heart_State = KO
inv12 : Sinus = Yes ∧ Disease_step8 ∈ {Definite_ischemia,
      Probable_ischemia, Digitalis_effect} ⇒
      Heart_State = KO
inv13 : Sinus = Yes ∧ Disease_step8 = Definite_ischemia ⇒
      Heart_State = KO
inv14 : Sinus = Yes ∧ Disease_step8 = Probable_ischemia ⇒
      Heart_State = KO
inv15 : Sinus = Yes ∧ Disease_step8.B ∈
      {Cardiomyopathy, other_nonspecific}
      ⇒ Heart_State = KO

```

From $inv9$ to $inv15$ represent abnormal state of heart due to finding some diseases. All these invariants are similar to the previous level of refinements. This refinement is very complex and we have formalised two alternate diagnosis for the ECG signal. We have introduced many events to assess the T-wave from the ECG signals and predict various diseases related to the T-wave. Events are $T_Wave_Assessment_Peaked_V123456$, $T_Wave_Assessment_Peaked_V12$, $T_Wave_Assessment_Peaked_V12_MI$, $T_Wave_Assessment_Flat$, $T_Wave_Assessment_Inverted_Yes$, $T_Wave_Assessment_Inverted_No$, $T_Wave_Assessment_Inverted_Yes_PM$, $T_Wave_Assessment_B$, $T_Wave_Assessment_B_DI$, $T_Inversion_Likely_Ischemia$, $T_Inversion_Diffuse_B$. All these events estimate the different kinds

of properties from the T-wave signal for obtaining the correct heart disease. A long textual representation for analysing the T-wave is given in [37].

6.2.8. Eighth Refinement : Assess Electrical Axis

After finding all kinds of information about abnormal ECG, it is also essential to check the electrical axis (see Table 2) using two simple clues:

- If leads I and aVF are upright, the axis is normal.
- The axis is perpendicular to the lead with the most equiphasic or smallest QRS deflection. Left-axis deviation and the commonly associated left anterior fascicular block are visible in ECG signal.

Most equiphasic lead	Lead perpendicular	Axis
		Lead I and aVF positive = normal axis
III	aVR	Normal = +30 degrees
aVL	II	Normal = +60 degrees Lead I positive and aVF negative = Left axis
II	aVL (QRS positive)	Left = -30 degrees
aVR	III (QRS negative)	Left = -60 degrees
I	aVF (QRS negative)	Left = -90 degrees Lead I negative and aVF positive = right axis
aVR	III (QRS positive)	Right = +120 degrees
II	aVL (QRS negative)	Right = +150 degrees

Table 2: Electrical Axis

This refinement is very essential refinement for the ECG interpretation because of the different angle of the ECG signal gives different output and angle based prediction can be changed [37]. So, for accuracy of the ECG interpretation electrical axis must be included. New variables *minAngle*, *maxAngle*, *Axis.Devi* and *Disease_step9* have been defined here for assessment of the electrical axis. A new variable *QRS_Axis_State* is defined as total function mapping from leads (LEADS) to *QRS_directions*. This function represents QRS-axis direction of the leads. Two invariants (*inv6* – *inv7*) represent safety properties in assessment of the correct axis. These invariants are verifying an abnormal state of heart (*KO*) using axis position.

```

inv1 : minAngle ∈ -90 .. 180
inv2 : maxAngle ∈ -90 .. 180
inv3 : Axis_Devi ∈ Axis_deviation
inv4 : Disease_step9 ∈ Disease_Codes_Step9
inv5 : QRS_Axis_State ∈ LEADS → QRS_directions
inv6 : Disease_step9 ∈ {LPFB, Dextrocardia, NV_MSEC} ∧
maxAngle = 180 ∧ minAngle = 110 ⇒ Heart_State = KO
inv7 : Disease_step9 ∈ {LAFB, MSCHD, Some_Form_VT, ED_OC}
∧ maxAngle = -90 ∧ minAngle = -30 ⇒ Heart_State = KO

```

In this refinement level, we introduce various events for assessing different kinds of features from 12 leads ECG signal corresponding to the angle. Following

events are introduced in this refinement: *Axis_Assessment_QRS_upright_Yes_Age_less_40*, *Axis_Assessment_QRS_upright_Yes-Age_gre_40*, *Axis_Assessment_QRS_upright_No_QRS_positive*, *Axis_Assessment_QRS_upright_No-QRS_negative*, *Misc_Disease_Step9_LAD*, *Misc_Disease_Step9_RAD*, *R_Q_Assessment_R_Abnormal_V56_axis_deviation*.

6.2.9. Ninth Refinement : Assess for miscellaneous conditions

There are lots of heart diseases and it is very difficult to predict everything. A lot of conditions make it more and more ambiguous. This refinement level keeps multiple miscellaneous conditions about the ECG interpretation [37]. Following conditions are given for miscellaneous conditions as follows:

- Artificial pacemakers: If electronic pacing is confirmed, usually no other diagnosis can be made from the ECG.
- Prolonged QT syndrome: See normal QT parameters listed in Table 3. No complicated formula is required for assessment of the QT intervals.

Heart rate (bpm)	Male	Female
45–65	<470	<480
66–100	<410	<430
>100	<360	<370

Table 3: Clinically useful approximation of upper limit of QT interval (ms.)

A variable *MC_Step10_Test_Needed* is declared to represent miscellaneous condition test as a boolean type *TRUE* or *FALSE*. Variable *Disease_step10* is introduced in this refinement to assess a set of diseases of miscellaneous conditions from the ECG signal. Next two invariants (*inv2* – *inv3*) represent the abnormality of the heart state (*KO*) in case of discovery of new miscellaneous diseases. In this refinement, we introduce only two events (*Miscellaneous_Conditions_Step10* and *Misc_Disease_Step10_Dextrocardia_Test*) to discover miscellaneous conditions from the ECG signal.

<pre> inv1 : MC_Step10_Test_Needed ∈ BOOL inv2 : Disease_step10 ∈ Misc_Disease_Codes_Step10 inv3 : Sinus = Yes ∧ Disease_step10 ∈ {Incomplete_RBBB, Long_QT, Hypokalemia, Digitalis_toxicity, Hypothermia, Electronic_pacing, Pericarditis, , Hypercalcemia} Electrical_alternans ⇒ Heart_State = KO inv4 : Sinus = Yes ∧ Disease_step9 = Dextrocardia ⇒ Heart_State = KO </pre>
--

6.2.10. Tenth Refinement : Assess Arrhythmias

This is the final refinement of the ECG interpretation of the system. In this refinement, we introduce different kinds of tachyarrhythmias and give the protocols for assessment as follows:

- Narrow complex tachycardia: Gives the differential diagnosis of narrow QRS complex tachycardia.
- Wide complex tachycardia: Gives the differential diagnosis of wide QRS complex tachycardia.

A new variable *NW_QRS_Tachycardia_RT_State* is defined to express QRS tachycardia regular or irregular state using *inv1*. Variable *Disease_step11* is introduced in this refinement to assess arrhythmias from the ECG signals. All rest of the invariants (*inv3 – inv9*) represent abnormal state (*KO*) of the heart after analysing arrhythmia and related disease. All invariants have similar kinds of properties. We introduce five new events to assess tachyarrhythmias from the 12-leads ECG signals in case of abnormal rhythm. Five events are *Rhythm_test_FALSE_Step11*, *Step11_N_QRS_Tachycardia_Regular*, *Step11_N_QRS_Tachycardia_Irregular*, *Step11_W_QRS_Tachycardia_Regular* and *Step11_W_QRS_Tachycardia_Irregular*.

```

inv1 : NW_QRS_Tachycardia_RT_State ∈
      NW_QRS_Tachycardia_RI
inv2 : Disease_step11 ∈ Misc_Disease_Codes_Step11
inv3 : Sinus = Yes ∧ Disease_step11 ∈
      {Ventricular_Premature_Beats, Nodal_Premature_Beats,
       Bradyarrhythmias, Narrow_QRS_Tachycardias,
       Wide_QRS_Tachycardias, Atrial_Premature_Beats}
      ⇒ Heart_State = KO

inv4 : Sinus = Yes ∧ Disease_step11_NW_QRST ∈
      {Sinus_Tachycardia, Supraventricular_Tachycardia,
       WPW_Syndrome_Orthodromic, Torsades_de_pointes,
       Atrial_Tachycardia, AF_Fixed_AV_Conduction, AVNRT,
       Ventricular_Tachycardia, WPW_Syndrome_Antidromic,
       AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti,
       AF_BBB_WPW_Synd_Antidromic}
      ⇒ Heart_State = KO

inv5 : Sinus = Yes ∧ Disease_step11_NW_QRST ∈
      {AF_Variable_AV_Conduction, AVNRT,
       AT_Paroxysmal_N_Paroxysmal, AT_Variable_AV_Block,
       AF_Fixed_AV_Conduction, WPW_Syndrome_OCMT,
       Sinus_Tachycardia, Multifocal_Atrial_Tachycardia,
       Atrial_Fibrillation}
      ⇒ Heart_State = KO

inv6 : NW_QRS_Tachycardia_RT_State = Regular ∧
      Disease_step11_NW_QRST ∈ {Sinus_Tachycardia,
       WPW_Syndrome_OCMT, AF_Fixed_AV_Conduction,
       AVNRT, AT_Paroxysmal_N_Paroxysmal}
      ⇒ Heart_State = KO

inv7 : NW_QRS_Tachycardia_RT_State = Irregular ∧
      Disease_step11_NW_QRST ∈ {Atrial_Fibrillation,
       AT_Variable_AV_Block, AF_Variable_AV_Conduction,
       Multifocal_Atrial_Tachycardia}
      ⇒ Heart_State = KO

inv8 : NW_QRS_Tachycardia_RT_State = Regular ∧
      Disease_step11_NW_QRST ∈ {Ventricular_Tachycardia,
       Sinus_Tachycardia, AF_Fixed_AV_Conduction,
       Supraventricular_Tachycardia, Atrial_Tachycardia,
       AVNRT, WPW_Syndrome_Antidromic,
       WPW_Syndrome_Orthodromic}
      ⇒ Heart_State = KO

inv9 : NW_QRS_Tachycardia_RT_State = Irregular ∧
      Disease_step11_NW_QRST ∈
      {AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti,
       Torsades_de_pointes, AF_BBB_WPW_Synd_Antidromic}
      ⇒ Heart_State = KO

```

In this report we have given only required safety properties in form invariants in all refinements. All these properties are derived from the original protocol to verify the correctness and consistency of the system. These properties are formulated through logic experts as well as cardiologist experts according to the original protocols. The main advantage of this technique is that if any property is not holding by the model, then it helps to find anomalies or to find missing parts of the model such as required conditions and parameters.

We have described here only summary informations about each refinement in form of basic description and required invariants of the ECG interpretation protocol using incremental refinement-based approach and omit detailed formalisation of events and proof details. To find complete formal representation

of the ECG interpretation protocol see [45].

7. Statistical Analysis and lesson learned

7.1. Statistical Analysis

All the proof obligations for all ten refinements are generated and proved using the RODIN prover [5]. The Table 4 shows statistics of the ECG interpretation protocol using refinement approach. In the table, the POs column represents the total number of proof obligations generated for each level. The interactive POs column represents the number of those proof obligations that have to be proved interactively. Those proof obligations that are not proved interactively are proved completely automatically by the prover. The complete development of the ECG interpretation protocol system results in 599 (100%) proof obligations, in which 343 (58%) are proved automatically by the RODIN tool. The remaining 256 (42%) proof obligations are proved interactively using RODIN tool. So, all the proofs are discharged completely automatic as well as interactive for all refinement levels. All these proofs are involved either by the complexity of the formal expression that proved by *do case* or finiteness constraints on a set of leads. The main interactive steps involved instantiating for total function of different feature of the ECG interpretation in every level of refinement. In order to guarantee the correctness of the system, we have established various invariants in stepwise refinement. All these invariants are derived from the original protocol to verify the correctness and consistency of the system under the guidance of the cardiologist expert. Most of the invariants are introduced for checking the abnormality of the features of the ECG signal. Detection of abnormal criteria, the heart shows surety of the particular disease or a set of diseases. A set of diseases are distinguished in next level of refinements.

Model	Total number of POs	Automatic Proof	Interactive Proof
Abstract Model	41	33(80%)	8(20%)
First Refinement	61	54(88%)	7(12%)
Second Refinement	41	38(92%)	3(8%)
Third Refinement	51	36(70%)	15(30%)
Fourth Refinement	60	35(58%)	25(42%)
Fifth Refinement	43	22(51%)	21(49%)
Sixth Refinement	38	14(36%)	24(64%)
Seventh Refinement	124	29(23%)	95(77%)
Eighth Refinement	52	30(57%)	22(43%)
Ninth Refinement	21	9(42%)	12(52%)
Tenth Refinement	67	43(64%)	24(36%)
Total	599	343(58%)	256(42%)

Table 4: Proof statistics

7.2. Lesson learned

The task of modelling of the ECG interpretation protocol in EVENT B has required a significant effort. It is a typical knowledge engineering task, where the knowledge is the original document, is transformed into the EVENT B formal notation, which provides a significant hierarchical structure for analysing the ECG interpretation protocol and diagnose different kinds of heart diseases. As result, the EVENT B ECG interpretation protocol specification is much more lengthy than the original text: the original ECG interpretation protocol. The complete formal specification of the ECG interpretation protocol in EVENT B is more than 200 pages.

We consider that logic-based modeling approach is very difficult to model a complex medical protocol. This approach has required a good understanding of logic as well as knowledge medical protocol. We have spend a lot of time with medical experts to understand the structure of the medical protocols for formalising purpose. For modelling the ECG protocol, we have consulted with cardiologist and medical experts. The formal model of ECG protocol is based on original protocol and checked by medical experts.

We cannot strictly say that the formal representation of the ECG interpretation protocol in EVENT B modeling language has contributed to the improvement of the original protocol. Most important contribution is refinements-based formal development of the ECG interpretation protocol and generate a new optimal way of the ECG interpretation protocol for diagnosing the ECG signal. The developed formal model is proved and verifying according to the given protocol properties as discussed in formal development. Furthermore, the EVENT B formalisation has served to disambiguate unclarities in original document that resulted from the modelling stage: a number of ambiguity and repetition diagnosis problems with original document are uncovered and resolved by refining the formal specification of the ECG interpretation protocol in EVENT B. The formal model can help to restructure the original document of guidelines and protocols.

The verification attempts have served to clarify any remaining problems in the original ECG interpretation protocol document. More importantly, we have shown that it is possible in practice to systematically analyse whether a protocol formalised in EVENT B complies with certain medically relevant properties. Various properties of the ECG interpretation protocol have been the object of formal verification using the EVENT B system, with different type of results. Mostly the given properties of the ECG interpretation protocol have been confirmed by the formal representation of the ECG interpretation protocol. However, in other cases verification is not simple and lots of ambiguous informations, i.e. it is not possible to complete the proof or further development of model due to ambiguity. We have introduced some additional assumptions with the help of cardiologist experts for describing the conditions needed to make the property true and added more conditions to remove the ambiguity. These assumptions are missing piece of information in medical protocol, which helps to improve the medical protocol. We have applied a pragmatic approach

to collect lots of informations through literature survey and medical experts's advises for finding the exact facts to introduce new assumptions and conditions for discharging all generated proof obligations.

For example, pieces of informations missing from the original ECG interpretation protocol like it is not given that how many leads should hold particular property during diagnosis. As per our solution we have applied test for particular properties in all leads. This results in a characterization of the circumstances under which the property holds. The obtained characterization is analyzed by medical experts under all possible conditions and it can be used either to redefine the property or to improve the original ECG interpretation protocol text by documenting the cases under which the property does (or does not) hold.

More importantly, numerous anomalies became apparent during the EVENT B modelling of the ECG interpretation protocol. Here we have used term anomaly to refer to any issue that are not able to represent satisfactory of the original ECG interpretation protocol. Some set of anomalies, which have found during the development of the system are described below. We have grouped all anomalies in three well known general categories: ambiguity, inconsistency and incompleteness.

7.2.1. Ambiguous

Ambiguous is well-known anomaly in area of formal representation and it is very hard to interpret. For instance, a problem we encountered while modelling the ECG interpretation protocol is determining whether the terms "ST-depression" and "ST-elevation" had the same meaning or not. These are terms that are used in the ECG interpretation original protocol, but not defined elsewhere. Similarly what is the difference between "ischemia", "Definite ischemia", "probable ischemia" and "likely ischemia".

In the ECG interpretation, there are 12 leads ECG signals, which are used for interpretation, but a lot of places in the original document not clarify in which lead the particular property should hold. Such kinds of informations are very ambiguous and give lots of confusions to model the system.

7.2.2. Inconsistencies

Inconsistencies are another kinds of anomalies which are always give conflicting results or different decisions on same patient data. The problems derived from inconsistent elements are very serious and as such must be avoided during development. The ECG interpretation protocol presents several inconsistencies. For instance, we found an inconsistency in form of applicable conditions in the ECG protocol. It expresses that the conditions are applicable for both "male" and "female" under some certain circumstances. However, elsewhere in the protocol an action is advised that these conditions of the protocol are not applicable for "female".

7.2.3. Incompleteness

Either missing pieces of information or insufficient information in original document are always related to the incompleteness anomaly. In either case,

incompleteness hinders a correct interpretation of guidelines and protocols. For example, the original protocol contains “normal variant” factors to be considered when assessing T-wave. However, what normal variant exactly means is missing in the protocol. As an example of insufficient information for “normal variant”, we provide the class of disease for further analysis the system.

8. Conclusions and future challenges

8.1. Conclusion

Refinement is a key concept for developing complex systems, since it starts with a very abstract model and incrementally adds new details to the set of requirements. We have outlined an incremental refinement-based approach for formalising medical protocols using RODIN tool. The approach we have taken is not specific to EVENT B. We believe a similar approach could be taken using others state-based notations such as ASM, TLA⁺ and Z etcetera. RODIN proof tool is used to generate the hundreds of proof obligations and to discharge those obligations automatically and interactively. Another key role of the tool is in helping us to discover appropriate gluing invariants to prove the refinements. In summary some key lessons are that incremental development with small refinement steps, appropriate abstractions at each level and powerful tool support are all invaluable in such kind of formal development.

In this report we have shown that formal representation of medical protocol. The formal model of medical protocol is verified and this verified model is not only feasible but also useful for improving the existing medical protocol. We have fully formalised a real-world medical protocols (ECG interpretation) in an incremental refinement-based formalisation process and we have used proof tools to systematically analyse whether the formalisation complies with certain medically relevant protocol properties. The formal verification process has discovered a number of anomalies which all are discussed in previous section. Throughout this process we have obtained the following concrete results:

- A formal specification language EVENT B that is used for modeling the complex system, is used to model medical practice protocols. EVENT B is general modeling language tool. The EVENT B is used to present a formal specification for a real-life medical protocols; ECG interpretation.
- The ECG interpretation protocol is formalised in EVENT B modeling language. The medical protocol ECG interpretation is used in our study has been developed in incremental way and finally transformed into a concrete formal representation. Each proved refinement level of the formal model of the protocol represents feasibility and correctness.
- In our formal verification process of the ECG interpretation, we have obtained a list of anomalies.
- Verification proofs for the ECG interpretation protocol and properties have proved using RODIN proof tool. Generated proof obligations and

proofs show that formal verification of the ECG interpretation protocols is feasible.

- Original protocol of the ECG is also based on some hierarchy, but in that hierarchy some diagnosis is repeating in multiple branches (see in [37]). We have also discovered an optimized hierarchical structure for the ECG interpretation efficiently using incremental refinement approach, which helps to diagnose more efficiently than old techniques and this obtained hierarchical structure is verified through medical experts.

The ECG interpretation protocol is very complex and it interprets various kinds of heart diseases. Improving quality of medical protocol using formal verification tool like highly mathematical based modelling languages; EVENT B, is the main contribution of our work. We have also discovered an hierarchical structure for the ECG interpretation efficiently that helps to discover a set of conditions that can be very helpful to diagnose particular disease an early stage of the diagnosis without using multiple diagnosis. Our hierarchical tree structure provides more concrete solutions for the ECG interpretation protocol and helps to improve the original ECG interpretation protocol. Our objective behind this work is that if any medical protocol is developed under particular circumstances to handle a set of specific properties according medical experts, formal verification can also meet whether the protocol actually complies with them. This has been the first attempt ever in verifying medical protocols with mathematical rigour with generalized formal modelling tool EVENT B. The main objective of this approach to test correctness and consistency of the medical protocol using refinement based incremental development. This approach is not only for diagnosis purpose but it may be applicable for covering a large group of other categories (i.e treatment, management, prevention, counseling, evaluation etc.)³ related to medical protocols.

8.2. Future challenges

This section will focus on some future challenges. First of all we discuss some challenges related to our work for applying formal techniques to improve medical protocol. We will also discuss some existing problems in medical domain, which leads to the challenge of “*living guidelines*” [2].

In this report we have shown that successful implementation for medical protocol improvement of using formal methods. We have completed the entire process of modelling and formalisation of the ECG interpretation protocol and properties, and discharged all generated proof obligations. We have also discovered some hierarchical structure for ECG diagnosis, which helps for improving the ECG protocol.

As we have seen in the entire article, several techniques like modelling, formalising and verifying are used to find anomalies in medical protocols. Some

³<http://www.guideline.gov/>

undecided issue that remain are: what kind of tools are applicable for finding anomalies; when do we need which type of techniques; would it be possible to use verification and validation only in the critical parts of the guideline, and how can we identify these critical parts. Main exiting problem with medical guideline or protocol is quickly changes in protocol within two-three years, which is indicated by Teije et all [2] as future challenges in their paper. After discussion with medical experts, we have found that it is an open problem in this area. However, from last few years medical scientific bodies are updating current guidelines and protocols on-line, and providing up to date information to all users.

We have used EVENT B modelling language for formalizing the medical protocols. Other languages like Glif, EON, Asbru, GUIDE, or others [10] are more popular languages for formal representation of guideline in medical domain. These languages can also detect anomalies in medical protocols but these are less formal then highly mathematical based modelling languages like EVENT B, VDM and TLA⁺ etcetera. Although, we expect that this would yield fewer anomalies during formal development of medical protocols because of the informal nature of these languages. In future we have planed to investigate other kinds of medical protocols using our refinement-based modeling approach. We have found that this approach is more applicable for rectifying the medical protocols as well as to obtain the optimum solutions for diagnosis using refinement based incremental approach rather then used any semi-formal techniques.

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Formal Model of ECG Interpretation using Event-B

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CONTEXT Leads_ctx

SETS

LEADS
HState
YesNoState

CONSTANTS

I
II
III
aVR
aVL
aVF
V1
V2
V3
V4
V5
V6
OK
K0
Yes
No

AXIOMS

axm1 : $LEADS = \{I, II, III, aVR, aVL, aVF, V1, V2, V3, V4, V5, V6\}$
axm2 : $\neg I = II$
axm3 : $\neg I = III$
axm4 : $\neg I = aVR$
axm5 : $\neg I = aVL$
axm6 : $\neg I = aVF$
axm7 : $\neg I = V1$
axm8 : $\neg I = V2$
axm9 : $\neg I = V3$
axm10 : $\neg I = V4$
axm11 : $\neg I = V5$
axm12 : $\neg I = V6$
axm13 : $\neg II = III$
axm14 : $\neg II = aVR$
axm15 : $\neg II = aVL$
axm16 : $\neg II = aVF$
axm17 : $\neg II = V1$

axm18 : $\neg II = V2$
 axm19 : $\neg II = V3$
 axm20 : $\neg II = V4$
 axm21 : $\neg II = V5$
 axm22 : $\neg II = V6$
 axm23 : $\neg III = aVR$
 axm24 : $\neg III = aVL$
 axm25 : $\neg III = aVF$
 axm26 : $\neg III = V1$
 axm27 : $\neg III = V2$
 axm28 : $\neg III = V3$
 axm29 : $\neg III = V4$
 axm30 : $\neg III = V5$
 axm31 : $\neg III = V6$
 axm32 : $\neg aVR = aVL$
 axm33 : $\neg aVR = aVF$
 axm34 : $\neg aVR = V1$
 axm35 : $\neg aVR = V2$
 axm36 : $\neg aVR = V3$
 axm37 : $\neg aVR = V4$
 axm38 : $\neg aVR = V5$
 axm39 : $\neg aVR = V6$
 axm40 : $\neg aVL = aVF$
 axm41 : $\neg aVL = V1$
 axm42 : $\neg aVL = V2$
 axm43 : $\neg aVL = V3$
 axm44 : $\neg aVL = V4$
 axm45 : $\neg aVL = V5$
 axm46 : $\neg aVL = V6$
 axm47 : $\neg aVF = V1$
 axm48 : $\neg aVF = V2$
 axm49 : $\neg aVF = V3$
 axm50 : $\neg aVF = V4$
 axm51 : $\neg aVF = V5$
 axm52 : $\neg aVF = V6$
 axm53 : $\neg V1 = V2$
 axm54 : $\neg V1 = V3$
 axm55 : $\neg V1 = V4$
 axm56 : $\neg V1 = V5$
 axm57 : $\neg V1 = V6$
 axm58 : $\neg V2 = V3$
 axm59 : $\neg V2 = V4$
 axm60 : $\neg V2 = V5$
 axm61 : $\neg V2 = V6$

axm62 : $\neg V3 = V4$
axm63 : $\neg V3 = V5$
axm64 : $\neg V3 = V6$
axm65 : $\neg V4 = V5$
axm66 : $\neg V4 = V6$
axm67 : $\neg V5 = V6$
axm68 : $HState = \{OK, KO\}$
axm69 : $\neg OK = KO$
axm70 : $YesNoState = \{Yes, No\}$
axm71 : $\neg Yes = No$

END

CONTEXT Disease_Codes.ctx

SETS

Disease_Codes_Step2
Disease_Codes_Step3
Disease_Codes_Step4

CONSTANTS

First_degree_AV_Block
LBBB
RBBB
A_RBBB
A_LBBB
WPW_Syndrome
Brugada_Syndrome
RV_Dysplasia
IVCD
Acute_inferior_MI
Acute_anterior_MI
STEMI
Troponin
CK_MB
Non_STEMI
Ischemia
NDS2
NDS3
NDS4

AXIOMS

axm1 : $Disease_Codes_Step2 = \{First_degree_AV_Block, LBBB, RBBB, NDS2\}$
axm2 : $\neg First_degree_AV_Block = LBBB$
axm3 : $\neg First_degree_AV_Block = RBBB$
axm43 : $\neg First_degree_AV_Block = NDS2$
axm4 : $\neg LBBB = RBBB$
axm44 : $\neg LBBB = NDS2$
axm45 : $\neg RBBB = NDS2$
axm5 : $Disease_Codes_Step3 = \{A_RBBB, A_LBBB, WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, IVCD, NDS3\}$
No. of Disease Step 3 (NDS3)
axm6 : $\neg A_RBBB = A_LBBB$
axm7 : $\neg A_RBBB = WPW_Syndrome$
axm8 : $\neg A_RBBB = Brugada_Syndrome$
axm9 : $\neg A_RBBB = RV_Dysplasia$

axm10 : $\neg A_RBBB = IVCD$
 axm46 : $\neg A_RBBB = NDS3$
 axm11 : $\neg A_LBBB = WPW_Syndrome$
 axm12 : $\neg A_LBBB = Brugada_Syndrome$
 axm13 : $\neg A_LBBB = RV_Dysplasia$
 axm14 : $\neg A_LBBB = IVCD$
 axm47 : $\neg A_LBBB = NDS3$
 axm15 : $\neg WPW_Syndrome = Brugada_Syndrome$
 axm16 : $\neg WPW_Syndrome = RV_Dysplasia$
 axm17 : $\neg WPW_Syndrome = IVCD$
 axm48 : $\neg WPW_Syndrome = NDS3$
 axm18 : $\neg Brugada_Syndrome = RV_Dysplasia$
 axm19 : $\neg Brugada_Syndrome = IVCD$
 axm49 : $\neg Brugada_Syndrome = NDS3$
 axm20 : $\neg RV_Dysplasia = IVCD$
 axm50 : $\neg RV_Dysplasia = NDS3$
 axm51 : $\neg IVCD = NDS3$
 axm21 : $Disease_Codes_Step4 = \{Acute_inferior_MI, Acute_anterior_MI, STEMI, Troponin, CK_MB, Non_STEMI, Ischemia, NDS4\}$
 axm22 : $\neg Acute_inferior_MI = Acute_anterior_MI$
 axm23 : $\neg Acute_inferior_MI = STEMI$
 axm24 : $\neg Acute_inferior_MI = Troponin$
 axm25 : $\neg Acute_inferior_MI = CK_MB$
 axm26 : $\neg Acute_inferior_MI = Non_STEMI$
 axm27 : $\neg Acute_inferior_MI = Ischemia$
 axm52 : $\neg Acute_inferior_MI = NDS4$
 axm28 : $\neg Acute_anterior_MI = STEMI$
 axm29 : $\neg Acute_anterior_MI = Troponin$
 axm30 : $\neg Acute_anterior_MI = CK_MB$
 axm31 : $\neg Acute_anterior_MI = Non_STEMI$
 axm32 : $\neg Acute_anterior_MI = Ischemia$
 axm53 : $\neg Acute_anterior_MI = NDS4$
 axm33 : $\neg STEMI = Troponin$
 axm34 : $\neg STEMI = CK_MB$
 axm35 : $\neg STEMI = Non_STEMI$
 axm36 : $\neg STEMI = Ischemia$
 axm54 : $\neg STEMI = NDS4$
 axm37 : $\neg Troponin = CK_MB$
 axm38 : $\neg Troponin = Non_STEMI$
 axm39 : $\neg Troponin = Ischemia$
 axm56 : $\neg Troponin = NDS4$
 axm40 : $\neg CK_MB = Non_STEMI$
 axm41 : $\neg CK_MB = Ischemia$
 axm55 : $\neg CK_MB = NDS4$
 axm42 : $\neg Non_STEMI = Ischemia$
 axm57 : $\neg Non_STEMI = NDS4$
 axm58 : $\neg Ischemia = NDS4$

END

MACHINE Step1

SEES Leads_ctx

VARIABLES

RR_Int_equidistant RR Interval
 PP_Int_equidistant PP Interval
 P_Positive P wave positive or negative
 Sinus Sinus Rhythm
 PP_Interval
 RR_Interval

INVARIANTS

inv1 : $RR_Int_equidistant \in LEADS \rightarrow BOOL$
 RR intervals are equidistant

inv2 : $PP_Int_equidistant \in LEADS \rightarrow BOOL$
 PP intervals are equidistant

inv3 : $P_Positive \in LEADS \rightarrow BOOL$
 P wave positive

inv4 : $Sinus \in YesNoState$
 Sinus State

inv5 : $PP_Interval \in LEADS \rightarrow \mathbb{N}$

inv6 : $RR_Interval \in LEADS \rightarrow \mathbb{N}$

inv7 : $P_Positive(II) = FALSE \Rightarrow Sinus = No$

inv8 : $((\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP_Int_equidistant(l) = FALSE \vee$
 $RR_Int_equidistant(l) = FALSE \vee$
 $RR_Interval(l) \neq PP_Interval(l))$
 \vee
 $P_Positive(II) = FALSE) \Rightarrow Sinus = No$

inv9 : $Sinus = Yes \Rightarrow ((\exists l \cdot l \in \{II, V1, V2\} \wedge PP_Int_equidistant(l) = TRUE \wedge$
 $RR_Int_equidistant(l) = TRUE \wedge$
 $RR_Interval(l) = PP_Interval(l))$
 \wedge
 $P_Positive(II) = TRUE)$

EVENTS

Initialisation

begin

act1 : $RR_Int_equidistant : \in LEADS \rightarrow BOOL$

act2 : $PP_Int_equidistant : \in LEADS \rightarrow BOOL$

act3 : $P_Positive : \in LEADS \rightarrow BOOL$

act4 : $Sinus := No$

act5 : $PP_Interval : \in LEADS \rightarrow \mathbb{N}$

act6 : $RR_Interval : \in LEADS \rightarrow \mathbb{N}$

end

Event $Rhythm_test_TRUE \hat{=} Sinus Rhythm$

```

when
  grd4 : ( $\exists l \cdot l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
     $RR\_Int\_equidistant(l) = TRUE \wedge$ 
     $RR\_Interval(l) = PP\_Interval(l)$ 
     $\wedge$ 
     $P\_Positive(II) = TRUE$ 
  then
    act1 : Sinus := Yes
  end
Event Rhythm_test_FALSE  $\hat{=}$ 
  Abnormal Rhythm
when
  grd2 : ( $\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \vee$ 
     $RR\_Int\_equidistant(l) = FALSE \vee$ 
     $RR\_Interval(l) \neq PP\_Interval(l)$ 
     $\vee$ 
     $P\_Positive(II) = FALSE$ 
  then
    act1 : Sinus := No
  end
END

```

An Event-B Specification of Step1_Rate_Ref
Generated Date: 25 Nov 2010 @ 03:39:01 PM

MACHINE Step1_Rate_Ref

REFINES Step1

SEES Leads_ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PP_Interval
RR_Interval

INVARIANTS

inv1: $Heart_Rate \in 1 .. 300$
inv2: $Heart_State \in HState$
inv3: $Heart_Rate \in 60 .. 100 \wedge Sinus = Yes \Rightarrow Heart_State = OK$
inv5: $Heart_Rate \in 1 .. 300 \setminus 60 .. 100 \wedge Sinus = Yes \Rightarrow Heart_State = KO$
inv6: $Heart_Rate \in 60 .. 100 \wedge Sinus = No \Rightarrow Heart_State = KO$

EVENTS

Initialisation

begin
act1: $RR_Int_equidistant : \in LEADS \rightarrow BOOL$
act2: $PP_Int_equidistant : \in LEADS \rightarrow BOOL$
act3: $P_Positive : \in LEADS \rightarrow BOOL$
act4: $Sinus := No$
act5: $PP_Interval : \in LEADS \rightarrow \mathbb{N}$
act6: $RR_Interval : \in LEADS \rightarrow \mathbb{N}$
act7: $Heart_Rate : \in 1 .. 300$
act8: $Heart_State := KO$

end

Event $Rhythm_test_TRUE \hat{=} Sinus Rhythm with Normal Rate$

refines $Rhythm_test_TRUE$

any

rate

where

grd1: $(\exists l.l \in \{II, V1, V2\} \wedge PP_Int_equidistant(l) = TRUE \wedge$
 $RR_Int_equidistant(l) = TRUE \wedge$
 $RR_Interval(l) = PP_Interval(l))$
 \wedge
 $P_Positive(II) = TRUE$


```

    grd5 : rate ∈ 60 .. 100
           60..100 is the range of normal heart rate
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := OK
  end
Event Rhythm_test_FALSE ≐
  Abnormal Rhythm with Rate
refines Rhythm_test_FALSE
  any
    rate
  where
    grd1 : (∀l·l ∈ {II, V1, V2} ⇒ PP_Int_equidistant(l) = FALSE ∨
            RR_Int_equidistant(l) = FALSE ∨
            RR_Interval(l) ≠ PP_Interval(l))
            ∨
            P_Positive(II) = FALSE
    grd2 : rate ∈ 1 .. 300
  then
    act1 : Sinus := No
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end
Event Rhythm_test_TRUE_Rate ≐
  Sinus Rhythm with abnormal Rate
refines Rhythm_test_TRUE
  any
    rate
  where
    grd1 : (∃l·l ∈ {II, V1, V2} ∧ PP_Int_equidistant(l) = TRUE ∧
            RR_Int_equidistant(l) = TRUE ∧
            RR_Interval(l) = PP_Interval(l))
            ∧
            P_Positive(II) = TRUE
    grd5 : rate ∈ 1 .. 300 \ 60 .. 100
           60..100 is the range of normal heart rate, so rest of no. is abnormal
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end
END

```

An Event-B Specification of Step2_PR.Blocks_Ref
Generated Date: 25 Nov 2010 @ 03:39:03 PM

MACHINE Step2_PR.Blocks_Ref

REFINES Step1_Rate_Ref

SEES Leads_ctx, Disease_Codes_ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
PP_Interval
RR_Interval

INVARIANTS

inv1 : $PR_Int \in 120 .. 250$
inv2 : $Disease_step2 \in Disease_Codes_Step2$
inv3 : $QRS_Int \in 50 .. 150$
inv4 : $Sinus = Yes \wedge PR_Int > 200 \wedge Disease_step2 = First_degree_AV_Block$
 $\Rightarrow Heart_State = KO$
inv5 : $Sinus = Yes \wedge QRS_Int \geq 120 \wedge Disease_step2 \in \{LBBB, RBBB\}$
 $\Rightarrow Heart_State = KO$
inv7 : $Heart_Rate \in 60 .. 100 \wedge Sinus = Yes \wedge PR_Int \leq 200 \wedge QRS_Int < 120$
 $\Rightarrow Heart_State = OK$

EVENTS

Initialisation

extended

begin

act1 : $RR_Int_equidistant : \in LEADS \rightarrow BOOL$
act2 : $PP_Int_equidistant : \in LEADS \rightarrow BOOL$
act3 : $P_Positive : \in LEADS \rightarrow BOOL$
act4 : $Sinus := No$
act5 : $PP_Interval : \in LEADS \rightarrow \mathbb{N}$
act6 : $RR_Interval : \in LEADS \rightarrow \mathbb{N}$
act7 : $Heart_Rate : \in 1 .. 300$
act8 : $Heart_State := KO$
act9 : $PR_Int := 120$
act10 : $Disease_step2 := NDS2$
act11 : $QRS_Int := 50$

end

Event *Rhythm_test_TRUE* $\hat{=}$
Sinus Rhythm with Normal Rate

refines *Rhythm_test_TRUE*

any
rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \wedge PP_Int_equidistant(l) = TRUE \wedge$
 $RR_Int_equidistant(l) = TRUE \wedge$
 $RR_Interval(l) = PP_Interval(l))$
 \wedge
 $P_Positive(II) = TRUE$

grd4 : *rate* $\in 60 .. 100$
60..100 is the range of normal heart rate

grd5 : $PR_Int \leq 200$
Heart is Normal if $PR \leq 200$ $QRS_Int \leq 120$
 $HeartisNormalifQRS < 120$

then

act1 : *Sinus* := *Yes*
act2 : *Heart_Rate* := *rate*
act3 : *Heart_State* := *OK*

end

Event *Rhythm_test_FALSE* $\hat{=}$
Abnormal Rhythm with Rate

extends *Rhythm_test_FALSE*

any
rate

where

grd1 : $(\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP_Int_equidistant(l) = FALSE \vee$
 $RR_Int_equidistant(l) = FALSE \vee$
 $RR_Interval(l) \neq PP_Interval(l))$
 \vee
 $P_Positive(II) = FALSE$

grd2 : *rate* $\in 1 .. 300$

then

act1 : *Sinus* := *No*
act2 : *Heart_Rate* := *rate*
act3 : *Heart_State* := *KO*

end

Event *Rhythm_test_TRUE_Rate* $\hat{=}$
Sinus Rhythm with abnormal Rate

refines *Rhythm_test_TRUE_Rate*

any
rate

where

```

    grd1 : ( $\exists l \cdot l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
             $RR\_Int\_equidistant(l) = TRUE \wedge$ 
             $RR\_Interval(l) = PP\_Interval(l)$ 
             $\wedge$ 
             $P\_Positive(II) = TRUE$ 
    grd5 :  $rate \in 1 .. 300 \setminus 60 .. 100$ 
           60..100 is the range of normal heart rate, so rest of no. is abnormal
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end

Event PR_Test  $\hat{=}$ 
  PR Interval Test

  any
    pr
  where
    grd1 :  $pr \in 120 .. 220$ 
           time interval in (ms.)
    grd2 :  $pr > 200$ 
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
  then
    act1 : PR_Int := pr
    act2 : Disease_step2 := First_degree_AV_Block
  end

Event QRS_Test  $\hat{=}$ 
  QRS Complex Interval Test

  any
    qrs
  where
    grd1 :  $qrs \in 50 .. 150$ 
    grd2 :  $qrs \geq 120$ 
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 :  $|Disease\_step2' \in \{LBBB, RBBB\}$ 
  end

END

```

MACHINE Step2_Blocks_Ref

REFINES Step2_PR_Blocks_Ref

SEES Leads_ctx, Disease_Codes_ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
Small_R_QS A small R or QS wave in V1 and V2
Slurred_S_duration Slurred S duration
PP_Interval
RR_Interval

INVARIANTS

inv1 : $M_Shape_Complex \in LEADS \rightarrow BOOL$
inv2 : $Slurred_S \in LEADS \rightarrow BOOL$
inv3 : $Notched_R \in LEADS \rightarrow BOOL$
inv4 : $Small_R_QS \in LEADS \rightarrow BOOL$
inv5 : $Slurred_S_duration \in LEADS \rightarrow \mathbb{N}_1$
inv6 : $Sinus = Yes \wedge Disease_step2 = First_degree_AV_Block \Rightarrow Heart_State = KO$
inv7 : $Sinus = Yes \wedge Disease_step2 = LBBB \Rightarrow Heart_State = KO$
inv8 : $Sinus = Yes \wedge Disease_step2 = RBBB \Rightarrow Heart_State = KO$

EVENTS

Initialisation

extended

begin

act1 : $RR_Int_equidistant \in LEADS \rightarrow BOOL$
act2 : $PP_Int_equidistant \in LEADS \rightarrow BOOL$
act3 : $P_Positive \in LEADS \rightarrow BOOL$
act4 : $Sinus := No$
act5 : $PP_Interval \in LEADS \rightarrow \mathbb{N}$
act6 : $RR_Interval \in LEADS \rightarrow \mathbb{N}$
act7 : $Heart_Rate \in 1..300$

```

act8 : Heart_State := KO
act9 : PR_Int := 120
act10 : Disease_step2 := NDS2
act11 : QRS_Int := 50
act12 : Notched_R :∈ LEADS → BOOL
act13 : Small_R_QS :∈ LEADS → BOOL
act14 : Slurred_S_duration :∈ LEADS → ℕ1
act15 : M_Shape_Complex :∈ LEADS → BOOL
act16 : Slurred_S :∈ LEADS → BOOL

end

Event Rhythm_test.TRUE ≐
  Sinus Rhythm with Normal Rate

refines Rhythm_test.TRUE

any
  rate
where
  grd1 : (∃l.l ∈ {II, V1, V2} ∧ PP_Int_equidistant(l) = TRUE ∧
    RR_Int_equidistant(l) = TRUE ∧
    RR_Interval(l) = PP_Interval(l))
    ∧
    P_Positive(II) = TRUE
  grd4 : rate ∈ 60 .. 100
    60..100 is the range of normal heart rate
  grd5 : PR_Int ≤ 200
    Heart is Normal if PR ≤ 200 QRS_Int ; 120
    HeartisNormalifQRS < 120
  grd6 : Disease_step2 = NDS2
then
  act1 : Sinus := Yes
  act2 : Heart_Rate := rate
  act3 : Heart_State := OK
end

Event Rhythm_test.FALSE ≐
  Abnormal Rhythm with Rate

extends Rhythm_test.FALSE

any
  rate
where
  grd1 : (∀l.l ∈ {II, V1, V2} ⇒ PP_Int_equidistant(l) = FALSE ∨
    RR_Int_equidistant(l) = FALSE ∨
    RR_Interval(l) ≠ PP_Interval(l))
    ∨
    P_Positive(II) = FALSE
  grd2 : rate ∈ 1 .. 300
then
  act1 : Sinus := No
  act2 : Heart_Rate := rate

```

```

        act3 : Heart_State := KO
    end

Event Rhythm_test_TRUE_Rate  $\hat{=}$ 
    Sinus Rhythm with abnormal Rate

extends Rhythm_test_TRUE_Rate

    any
        rate
    where
        grd1 : ( $\exists l \cdot l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
            RR_Int_equidistant(l) = TRUE  $\wedge$ 
            RR_Interval(l) = PP_Interval(l))
             $\wedge$ 
            P_Positive(II) = TRUE
        grd5 : rate  $\in 1..300 \setminus 60..100$ 
            60..100 is the range of normal heart rate, so rest of no. is abnormal
    then
        act1 : Sinus := Yes
        act2 : Heart_Rate := rate
        act3 : Heart_State := KO
    end

Event PR_Test  $\hat{=}$ 
    PR Interval Test

extends PR_Test

    any
        pr
    where
        grd1 : pr  $\in 120..220$ 
            time interval in (ms.)
        grd2 : pr > 200
        grd3 : Sinus = Yes
        grd4 : Heart_State = KO
    then
        act1 : PR_Int := pr
        act2 : Disease_step2 := First_degree_AV_Block
    end

Event QRS_Test_LBBB  $\hat{=}$ 
    QRS Complex Interval Test

refines QRS_Test

    any
        qrs
    where
        grd1 : qrs  $\in 50..150$ 
        grd2 : qrs  $\geq 120$ 
        grd3 : Sinus = Yes
        grd4 : Heart_State = KO

```

```

    grd5 : Notched_R(I) = TRUE ∧
           Notched_R(V5) = TRUE ∧
           Notched_R(V6) = TRUE
           Right Bundle Branch Block (RBBB)
    grd6 : Small_R_QS(V1) = TRUE ∧
           Small_R_QS(V2) = TRUE

  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := LBBB
  end

Event QRS_Test_RBBB ≐
  Right Bundle Branch Block (RBBB)

refines QRS_Test

  any
    qrs
  where
    grd1 : qrs ∈ 50 .. 150
    grd2 : qrs ≥ 120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : M_Shape_Complex(V1) = TRUE ∧
           M_Shape_Complex(V2) = TRUE
    grd7 : Slurred_S(I) = TRUE ∧
           Slurred_S(V5) = TRUE ∧
           Slurred_S(V6) = TRUE
    grd8 : Slurred_S_duration(I) > 40 ∧
           Slurred_S_duration(V5) > 40 ∧
           Slurred_S_duration(V6) > 40

  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := RBBB
  end

end

END

```


An Event-B Specification of Step3
Generated Date: 25 Nov 2010 @ 03:39:09 PM

MACHINE Step3

REFINES Step2.Blocks_Ref

SEES Leads_ctx, Disease_Codes_ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
PP_Interval
RR_Interval
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
Small_R_QS A small R or QS wave in V1 and V2
Slurred_S_duration Slurred S duration
Delta_Wave Delta Wave
Disease_step3
ST_elevation ST segment elevation (Coved or Saddle-back)
Epsilon_Wave Epsilon Wave or (a terminal notch in the QRS)

INVARIANTS

inv1: $\Delta_Wave \in \mathbb{N}$
inv2: $Disease_step3 \in Disease_Codes_Step3$
inv3: $Sinus = Yes \wedge Disease_step3 = WPW_Syndrome \Rightarrow Heart_State = KO$
inv4: $ST_elevation \in LEADS \rightarrow BOOL$
inv5: $Sinus = Yes \wedge Disease_step3 = Brugada_Syndrome \Rightarrow Heart_State = KO$
inv6: $Epsilon_Wave \in LEADS \rightarrow BOOL$
inv7: $Sinus = Yes \wedge Disease_step3 = RV_Dysplasia \Rightarrow Heart_State = KO$
inv8: $Sinus = Yes \wedge Disease_step3 = IVCD \Rightarrow Heart_State = KO$

EVENTS

Initialisation

extended

begin

act1: $RR_Int_equidistant \in LEADS \rightarrow BOOL$
act2: $PP_Int_equidistant \in LEADS \rightarrow BOOL$

```

act3 : P_Positive :∈ LEADS → BOOL
act4 : Sinus := No
act5 : PP_Interval :∈ LEADS → ℕ
act6 : RR_Interval :∈ LEADS → ℕ
act7 : Heart_Rate :∈ 1 .. 300
act8 : Heart_State := KO
act9 : PR_Int := 120
act10 : Disease_step2 := NDS2
act11 : QRS_Int := 50
act12 : Notched_R :∈ LEADS → BOOL
act13 : Small_R_QS :∈ LEADS → BOOL
act14 : Slurred_S_duration :∈ LEADS → ℕ1
act15 : M_Shape_Complex :∈ LEADS → BOOL
act16 : Slurred_S :∈ LEADS → BOOL
act17 : ST_elevation :∈ LEADS → BOOL
act18 : Epsilon_Wave :∈ LEADS → BOOL
act19 : Delta_Wave := 0
act20 : Disease_step3 := NDS3

end

Event Rhythm_test_TRUE ≐
  Sinus Rhythm with Normal Rate

refines Rhythm_test_TRUE

  any
    rate
  where
    grd1 : (∃l.l ∈ {II, V1, V2} ∧ PP_Int_equidistant(l) = TRUE ∧
      RR_Int_equidistant(l) = TRUE ∧
      RR_Interval(l) = PP_Interval(l))
      ∧
      P_Positive(II) = TRUE
    grd4 : rate ∈ 60 .. 100
      60..100 is the range of normal heart rate
    grd5 : PR_Int ≤ 200
      Heart is Normal if PR ≤ 200 QRS_Int ; 120
      Heart is Normal if QRS < 120
    grd7 : Disease_step2 = NDS2
    grd8 : Disease_step3 = NDS3
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := OK
  end

Event Rhythm_test_FALSE ≐
  Abnormal Rhythm with Rate

extends Rhythm_test_FALSE

  any
    rate

```

```

where
  grd1 : ( $\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \vee$ 
    RR_Int_equidistant(l) = FALSE  $\vee$ 
    RR.Interval(l)  $\neq$  PP.Interval(l))
     $\vee$ 
    P_Positive(II) = FALSE
  grd2 : rate  $\in$  1 .. 300
then
  act1 : Sinus := No
  act2 : Heart_Rate := rate
  act3 : Heart_State := KO
end

Event Rhythm_test_TRUE_Rate  $\hat{=}$ 
  Sinus Rhythm with abnormal Rate

refines Rhythm_test_TRUE_Rate

any
  rate
where
  grd1 : ( $\exists l \cdot l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
    RR_Int_equidistant(l) = TRUE  $\wedge$ 
    RR.Interval(l) = PP.Interval(l))
     $\wedge$ 
    P_Positive(II) = TRUE
  grd5 : rate  $\in$  1 .. 300  $\setminus$  60 .. 100
    60..100 is the range of normal heart rate, so rest of no. is abnormal
  grd6 : Disease_step3 = WPW_Syndrome  $\vee$  Disease_step3 = Brugada_Syndrome  $\vee$ 
    Disease_step3 = RV_Dysplasia  $\vee$  Disease_step3 = IVCD
then
  act1 : Sinus := Yes
  act2 : Heart_Rate := rate
  act3 : Heart_State := KO
end

Event PR_Test  $\hat{=}$ 
  PR Interval Test

extends PR_Test

any
  pr
where
  grd1 : pr  $\in$  120 .. 220
    time interval in (ms.)
  grd2 : pr > 200
  grd3 : Sinus = Yes
  grd4 : Heart_State = KO
then
  act1 : PR_Int := pr
  act2 : Disease_step2 := First_degree_AV_Block
end

```

```

Event QRS_Test_LBBB  $\hat{=}$ 
  QRS Complex Interval Test

refines QRS_Test_LBBB

  any
    qrs
  where
    grd1 : qrs  $\in$  50 .. 150
    grd2 : qrs  $\geq$  120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : Notched_R(I) = TRUE  $\wedge$ 
      Notched_R(V5) = TRUE  $\wedge$ 
      Notched_R(V6) = TRUE
      Right Bundle Branch Block (RBBB)
    grd6 : Small_R_QS(V1) = TRUE  $\wedge$ 
      Small_R_QS(V2) = TRUE

  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := LBBB

  end

Event QRS_Test_RBBB  $\hat{=}$ 
  Right Bundle Branch Block (RBBB)

refines QRS_Test_RBBB

  any
    qrs
  where
    grd1 : qrs  $\in$  50 .. 150
    grd2 : qrs  $\geq$  120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : M_Shape_Complex(V1) = TRUE  $\wedge$ 
      M_Shape_Complex(V2) = TRUE
    grd7 : Slurred_S(I) = TRUE  $\wedge$ 
      Slurred_S(V5) = TRUE  $\wedge$ 
      Slurred_S(V6) = TRUE
    grd8 : Slurred_S_duration(I) > 40  $\wedge$ 
      Slurred_S_duration(V5) > 40  $\wedge$ 
      Slurred_S_duration(V6) > 40

  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := RBBB

  end

Event QRS_Test_Atypical_RLBBB_WPW_Syndrome  $\hat{=}$ 
  QRS Test for Atypical LBBB RBBB

  any
    sympt

```

```

    d_wave
where
    grd1 : QRS_Int ≥ 110
    grd2 : sympt = A_RBBB ∨ sympt = A_LBBB
    grd3 : d_wave ∈ ℕ
    grd4 : (d_wave + PR_Int) ≤ 120
           Delta_Wave + PR ≤ 120 Heart_State = KO
then
    act2 : Delta_Wave := d_wave
    act3 : Disease_step3 := WPW_Syndrome
end
Event QRS_Test_Atypical_RBBB_Brugada_Syndrome ≐
    Atypical_RBBB but WPW Excluded and no slurred S wave in V5 and V6
any
    sympt
    dis
where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int ≥ 110
    grd4 : Slurred_S(V5) = FALSE ∧
           Slurred_S(V6) = FALSE
    grd5 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, NDS3}
    grd6 : ST_elevation(V1) = TRUE ∧
           ST_elevation(V2) = TRUE
    grd7 : Sinus = Yes
then
    act1 : Disease_step3 := Brugada_Syndrome
end
Event QRS_Test_Atypical_RBBB_RV_Dysplasia ≐
    Right_Ventricular_Dysplasia
any
    sympt
    dis
where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int ≥ 110
    grd4 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, NDS3}
    grd5 : Epsilon_Wave(V1) = TRUE ∧
           Epsilon_Wave(V3) = TRUE
then
    act1 : Disease_step3 := RV_Dysplasia
end
Event QRS_Test_Atypical_RBBB_IVCD ≐
    IVCD_diagnosis

```

```
any
  dis
where
  grd1 :  $QRS\_Int \geq 110$ 
  grd2 :  $dis \in Disease\_Codes\_Step3 \setminus \{WPW\_Syndrome, Brugada\_Syndrome, RV\_Dysplasia, NDS3\}$ 
  grd3 :  $Heart\_State = KO$ 
then
  act1 :  $Disease\_step3 := IVCD$ 
end
END
```

An Event-B Specification of Step4
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MACHINE Step4

REFINES Step3

SEES Leads_ctx, Disease_Codes_ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
PP_Interval
RR_Interval
Small_R_QS A small R or QS wave in V1 and V2
Slurred_S_duration Slurred S duration
Delta_Wave Delta Wave
Disease_step3
ST_elevation ST segment elevation (Coved or Saddle-back)
Epsilon_Wave Epsilon Wave or (a terminal notch in the QRS)
ST_seg_ele ST segment for elevation 1mm=0.1mV
Disease_step4

INVARIANTS

inv1: $ST_seg_ele \in LEADS \rightarrow \mathbb{N}$
inv2: $Disease_step4 \in Disease_Codes_Step4$

EVENTS

Initialisation

begin
act1: $RR_Int_equidistant : \in LEADS \rightarrow BOOL$
act2: $PP_Int_equidistant : \in LEADS \rightarrow BOOL$
act3: $P_Positive : \in LEADS \rightarrow BOOL$
act4: $Sinus := No$
act5: $PP_Interval : \in LEADS \rightarrow \mathbb{N}$
act6: $RR_Interval : \in LEADS \rightarrow \mathbb{N}$
act7: $Heart_Rate : \in 1 .. 300$
act8: $Heart_State := KO$

```

act9 : PR_Int := 120
act10 : Disease_step2 := NDS2
act11 : QRS_Int := 50
act12 : Notched_R :∈ LEADS → BOOL
act13 : Small_R_QS :∈ LEADS → BOOL
act14 : Slurred_S_duration :∈ LEADS → ℕ1
act15 : M_Shape_Complex :∈ LEADS → BOOL
act16 : Slurred_S :∈ LEADS → BOOL
act17 : ST_elevation :∈ LEADS → BOOL
act18 : Epsilon_Wave :∈ LEADS → BOOL
act19 : Delta_Wave := 0
act20 : Disease_step3 := NDS3
act21 : ST_seg_ele :∈ LEADS → ℕ
act22 : Disease_step4 := NDS4

end

Event Rhythm_test_TRUE ≐
  Sinus Rhythm with Normal Rate

extends Rhythm_test_TRUE

any
  rate
where
  grd1 : (∃l. l ∈ {II, V1, V2} ∧ PP_Int.equidistant(l) = TRUE ∧
    RR_Int.equidistant(l) = TRUE ∧
    RR_Interval(l) = PP_Interval(l))
    ∧
    P_Positive(II) = TRUE
  grd4 : rate ∈ 60 .. 100
    60..100 is the range of normal heart rate
  grd5 : PR_Int ≤ 200
    Heart is Normal if PR ≤ 200 QRS_Int < 120
    HeartisNormalifQRS < 120
  grd6grd7 : Disease_step2 = NDS2
  grd8 : Disease_step3 = NDS3

then
  act1 : Sinus := Yes
  act2 : Heart_Rate := rate
  act3 : Heart_State := OK

end

Event Rhythm_test_FALSE ≐
  Abnormal Rhythm with Rate

extends Rhythm_test_FALSE

any
  rate
where
  grd1 : (∀l. l ∈ {II, V1, V2} ⇒ PP_Int.equidistant(l) = FALSE ∨
    RR_Int.equidistant(l) = FALSE ∨
    RR_Interval(l) ≠ PP_Interval(l))
    ∨
    P_Positive(II) = FALSE

```



```

    grd2 : rate ∈ 1 .. 300
  then
    act1 : Sinus := No
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end
Event Rhythm_test.TRUE_Rate ≐
  Sinus Rhythm with abnormal Rate
extends Rhythm_test.TRUE_Rate
  any
    rate
  where
    grd1 : (∃l·l ∈ {II, V1, V2} ∧ PP_Int.equidistant(l) = TRUE ∧
      RR_Int.equidistant(l) = TRUE ∧
      RR.Interval(l) = PP.Interval(l))
      ∧
      P_Positive(II) = TRUE
    grd5 : rate ∈ 1 .. 300 \ 60 .. 100
      60..100 is the range of normal heart rate, so rest of no. is abnormal
    grd6 : Disease_step3 = WPW.Syndrome ∨ Disease_step3 = Brugada.Syndrome ∨
      Disease_step3 = RV_Dysplasia ∨ Disease_step3 = IVCD
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end
Event PR_Test ≐
  PR Interval Test
extends PR_Test
  any
    pr
  where
    grd1 : pr ∈ 120 .. 220
      time interval in (ms.)
    grd2 : pr > 200
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
  then
    act1 : PR.Int := pr
    act2 : Disease_step2 := First_degree_AV_Block
  end
Event QRS_Test_LBBB ≐
  QRS Complex Interval Test
extends QRS_Test_LBBB
  any

```

```

    qrs
  where
    grd1 : qrs ∈ 50 .. 150
    grd2 : qrs ≥ 120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : Notched_R(I) = TRUE ∧
           Notched_R(V5) = TRUE ∧
           Notched_R(V6) = TRUE
           Right Bundle Branch Block (RBBB)
    grd6 : Small_R_QS(V1) = TRUE ∧
           Small_R_QS(V2) = TRUE

  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := LBBB
  end

Event QRS_Test_RBBB ≐
  Right Bundle Branch Block (RBBB)

refines QRS_Test_RBBB

  any
    qrs
  where
    grd1 : qrs ∈ 50 .. 150
    grd2 : qrs ≥ 120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : M_Shape_Complex(V1) = TRUE ∧
           M_Shape_Complex(V2) = TRUE
    grd7 : Slurred_S(I) = TRUE ∧
           Slurred_S(V5) = TRUE ∧
           Slurred_S(V6) = TRUE
    grd8 : Slurred_S_duration(I) > 40 ∧
           Slurred_S_duration(V5) > 40 ∧
           Slurred_S_duration(V6) > 40

  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := RBBB
  end

Event QRS_Test_Atypical_RLBBB_WPW_Syndrome ≐
  QRS Test for Atypical LBBB RBBB

extends QRS_Test_Atypical_RLBBB_WPW_Syndrome

  any
    sympt
    d_wave
  where
    grd1 : QRS_Int ≥ 110
    grd2 : sympt = A_RBBB ∨ sympt = A_LBBB

```

```

    grd3 : d_wave ∈ ℕ
    grd4 : (d_wave + PR.Int) ≤ 120
           Delta_Wave + PR ≤ 120 Heart_State = KO
  then
    act2 : Delta_Wave := d_wave
    act3 : Disease_step3 := WPW_Syndrome
  end

Event QRS_Test_Atypical_RBBB_Brugada_Syndrome ≐
  Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

refines QRS_Test_Atypical_RBBB_Brugada_Syndrome

  any
    sympt
    dis
  where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int ≥ 110
    grd4 : Slurred_S(V5) = FALSE ∧
           Slurred_S(V6) = FALSE
    grd5 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, NDS3}
    grd6 : ST_elevation(V1) = TRUE ∧
           ST_elevation(V2) = TRUE
    grd7 : Sinus = Yes
  then
    act1 : Disease_step3 := Brugada_Syndrome
  end

Event QRS_Test_Atypical_RBBB_RV_Dysplasia ≐
  Right Ventricular Dysplasia

extends QRS_Test_Atypical_RBBB_RV_Dysplasia

  any
    sympt
    dis
  where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int ≥ 110
    grd4 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, NDS3}
    grd5 : Epsilon_Wave(V1) = TRUE ∧
           Epsilon_Wave(V3) = TRUE
  then
    act1 : Disease_step3 := RV_Dysplasia
  end

Event QRS_Test_Atypical_RBBB_IVCD ≐
  IVCD diagnosis

extends QRS_Test_Atypical_RBBB_IVCD

```

```

any
  dis
where
  grd1 : QRS_Int ≥ 110
  grd2 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, NDS3}
  grd3 : Heart_State = KO
then
  act1 : Disease_step3 := IVCD
end

Event ST_seg_elevation_Yes ≐
ST segment elevation...

when
  grd1 : Heart_State = KO
  grd2 : Sinus = Yes
  grd3 :
    ∨
    ((∃ l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
    (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
    ∧
    (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
    ∧ l1 ≠ k1
    ∧
    (
    (l1 = V1 ∧ k1 = V2) ∨
    (l1 = V2 ∧ k1 = V3) ∨
    (l1 = V3 ∧ k1 = V4) ∨
    (l1 = V4 ∧ k1 = V5) ∨
    (l1 = V5 ∧ k1 = V6)
    )
    ))
1000 micrometr = 1mm = 0.1mV
then
  act1 : Disease_step4 : |Disease_step4' ∈ Disease_Codes_Step4
end

Event ST_seg_elevation_No ≐
ST segment elevation...

when
  grd1 : Heart_State = KO
  grd2 : Sinus = Yes
  grd3 :
    ∨
    (∀ l1 · l1 ∈ {II, III, aVF} ⇒
    (ST_elevation(l1) = FALSE ∧ ST_seg_ele(l1) < 1000))

    ∨ l1, k1 · l1 ∈ {II, III, aVF} ∧ k1 ∈ {II, III, aVF} ∧ (ST_elevation(l1) = FALSE ∧
    ST_elevation(k1) = FALSE) ∧ (ST_seg_ele(l1) < 1000 ∧ ST_seg_ele(k1) < 1000) ⇒ l1 ≠
    k1)
then
  act1 : Disease_step4 : |Disease_step4' ∈ Disease_Codes_Step4
end

END

```

MACHINE Step4_ST_MI_Ref

REFINES Step4

SEES Leads_ctx, Disease_Codes_ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
PP_Interval
RR_Interval
Small_R_QS A small R or QS wave in V1 and V2
Slurred_S_duration Slurred S duration
Delta_Wave Delta Wave
Disease_step3
ST_elevation ST segment elevation (Coved or Saddle-back)
Epsilon_Wave Epsilon Wave or (a terminal notch in the QRS)
ST_seg_ele ST segment for elevation 1mm=0.1mV
Disease_step4
ST_depression

INVARIANTS

inv1: $ST_depression \in LEADS \rightarrow \mathbb{N}$
inv2: $Sinus = Yes \wedge Disease_step4 \in \{Acute_inferior_MI, Acute_anterior_MI\} \Rightarrow Heart_State = KO$
inv3: $Sinus = Yes \wedge Disease_step4 = STEMI \Rightarrow Heart_State = KO$

EVENTS

Initialisation

begin
act1: $RR_Int_equidistant : \in LEADS \rightarrow BOOL$
act2: $PP_Int_equidistant : \in LEADS \rightarrow BOOL$
act3: $P_Positive : \in LEADS \rightarrow BOOL$
act4: $Sinus := No$
act5: $PP_Interval : \in LEADS \rightarrow \mathbb{N}$

```

act6 : RR_Interval :∈ LEADS → ℕ
act7 : Heart_Rate :∈ 1 .. 300
act8 : Heart_State := KO
act9 : PR_Int := 120
act10 : Disease_step2 := NDS2
act11 : QRS_Int := 50
act12 : Notched_R :∈ LEADS → BOOL
act13 : Small_R_QS :∈ LEADS → BOOL
act14 : Slurred_S_duration :∈ LEADS → ℕ1
act15 : M_Shape_Complex :∈ LEADS → BOOL
act16 : Slurred_S :∈ LEADS → BOOL
act17 : ST_elevation :∈ LEADS → BOOL
act18 : Epsilon_Wave :∈ LEADS → BOOL
act19 : Delta_Wave := 0
act20 : Disease_step3 := NDS3
act21 : ST_seg_ele :∈ LEADS → ℕ
act22 : Disease_step4 := NDS4
act57 : ST_depression :∈ LEADS → ℕ

end

Event Rhythm_test_TRUE ≐
  Sinus Rhythm with Normal Rate

refines Rhythm_test_TRUE

  any
    rate
  where
    grd1 : (∃l·l ∈ {II, V1, V2} ∧ PP_Int_equidistant(l) = TRUE ∧
      RR_Int_equidistant(l) = TRUE ∧
      RR_Interval(l) = PP_Interval(l))
      ∧
      P_Positive(II) = TRUE
    grd4 : rate ∈ 60 .. 100
      60..100 is the range of normal heart rate
    grd5 : PR_Int ≤ 200
      Heart is Normal if PR ≤ 200 QRS_Int ; 120
      HeartisNormalifQRS < 120
    grd6 : Disease_step2 = NDS2
    grd7 : Disease_step3 = NDS3
    grd8 : Disease_step4 = NDS4
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := OK
  end

Event Rhythm_test_FALSE ≐
  Abnormal Rhythm with Rate

extends Rhythm_test_FALSE

  any

```

```

    rate
  where
    grd1 : ( $\forall l. l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \vee$ 
      RR_Int_equidistant(l) = FALSE  $\vee$ 
      RR_Interval(l)  $\neq$  PP_Interval(l))
       $\vee$ 
      P_Positive(II) = FALSE
    grd2 : rate  $\in$  1 .. 300
  then
    act1 : Sinus := No
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end

Event Rhythm_test.TRUE.Rate  $\hat{=}$ 
  Sinus Rhythm with abnormal Rate

extends Rhythm_test.TRUE.Rate

  any
    rate
  where
    grd1 : ( $\exists l. l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
      RR_Int_equidistant(l) = TRUE  $\wedge$ 
      RR_Interval(l) = PP_Interval(l))
       $\wedge$ 
      P_Positive(II) = TRUE
    grd5 : rate  $\in$  1 .. 300  $\setminus$  60 .. 100
      60..100 is the range of normal heart rate, so rest of no. is abnormal
    grd6 : Disease_step3 = WPW_Syndrome  $\vee$  Disease_step3 = Brugada_Syndrome  $\vee$ 
      Disease_step3 = RV_Dysplasia  $\vee$  Disease_step3 = IVCD
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end

Event PR_Test  $\hat{=}$ 
  PR Interval Test

extends PR_Test

  any
    pr
  where
    grd1 : pr  $\in$  120 .. 220
      time interval in (ms.)
    grd2 : pr > 200
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
  then
    act1 : PR_Int := pr
    act2 : Disease_step2 := First_degree_AV_Block

```

```

    end

Event QRS_Test_LBBB  $\hat{=}$ 
    QRS Complex Interval Test

extends QRS_Test_LBBB

any
    qrs
where
    grd1 : qrs  $\in$  50 .. 150
    grd2 : qrs  $\geq$  120
    grd3 : Sinus = Yes
    grd4 : Heart.State = KO
    grd5 : Notched_R(I) = TRUE  $\wedge$ 
        Notched_R(V5) = TRUE  $\wedge$ 
        Notched_R(V6) = TRUE
        Right Bundle Branch Block (RBBB)
    grd6 : Small_R_QS(V1) = TRUE  $\wedge$ 
        Small_R_QS(V2) = TRUE

then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := LBBB
end

Event QRS_Test_RBBB  $\hat{=}$ 
    Right Bundle Branch Block (RBBB)

extends QRS_Test_RBBB

any
    qrs
where
    grd1 : qrs  $\in$  50 .. 150
    grd2 : qrs  $\geq$  120
    grd3 : Sinus = Yes
    grd4 : Heart.State = KO
    grd5 : M.Shape_Complex(V1) = TRUE  $\wedge$ 
        M.Shape_Complex(V2) = TRUE
    grd7 : Slurred_S(I) = TRUE  $\wedge$ 
        Slurred_S(V5) = TRUE  $\wedge$ 
        Slurred_S(V6) = TRUE
    grd8 : Slurred_S_duration(I) > 40  $\wedge$ 
        Slurred_S_duration(V5) > 40  $\wedge$ 
        Slurred_S_duration(V6) > 40

then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := RBBB
end

Event QRS_Test_Atypical_RLBBB-WPW_Syndrome  $\hat{=}$ 
    QRS Test for Atypical LBBB RBBB

extends QRS_Test_Atypical_RLBBB-WPW_Syndrome

```



```

any
  sympt
  d_wave
where
  grd1 : QRS_Int ≥ 110
  grd2 : sympt = A_RBBB ∨ sympt = A_LBBB
  grd3 : d_wave ∈ ℕ
  grd4 : (d_wave + PR_Int) ≤ 120
  Delta_Wave + PR ≤ 120 Heart_State = KO
then
  act2 : Delta_Wave := d_wave
  act3 : Disease_step3 := WPW_Syndrome
end

Event QRS_Test_Atypical_RBBB_Brugada_Syndrome ≐
  Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends QRS_Test_Atypical_RBBB_Brugada_Syndrome

any
  sympt
  dis
where
  grd1 : sympt = A_RBBB
  grd2 : Heart_State = KO
  grd3 : QRS_Int ≥ 110
  grd4 : Slurred_S(V5) = FALSE ∧
    Slurred_S(V6) = FALSE
  grd5 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, NDS3}
  grd6 : ST_elevation(V1) = TRUE ∧
    ST_elevation(V2) = TRUE
  grd7 : Sinus = Yes
then
  act1 : Disease_step3 := Brugada_Syndrome
end

Event QRS_Test_Atypical_RBBB_RV_Dysplasia ≐
  Right Ventricular Dysplasia

extends QRS_Test_Atypical_RBBB_RV_Dysplasia

any
  sympt
  dis
where
  grd1 : sympt = A_RBBB
  grd2 : Heart_State = KO
  grd3 : QRS_Int ≥ 110
  grd4 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, NDS3}
  grd5 : Epsilon_Wave(V1) = TRUE ∧
    Epsilon_Wave(V3) = TRUE
then

```

```

        act1 : Disease_step3 := RV_Dysplasia
    end

Event QRS_Test_Atypical_RBBB_IVCD  $\hat{=}$ 
    IVCD diagnosis

extends QRS_Test_Atypical_RBBB_IVCD

    any
        dis
    where
        grd1 : QRS_Int  $\geq$  110
        grd2 : dis  $\in$  Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, NDS3}
        grd3 : Heart_State = KO
    then
        act1 : Disease_step3 := IVCD
    end

Event ST_seg_elevation_YES  $\hat{=}$ 
    ST segment elevation...

refines ST_seg_elevation_Yes

    when
        grd1 : Heart_State = KO
        grd2 : Sinus = Yes
        grd3 :
             $\vee$ 
            (( $\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
            (ST_elevation(l1) = TRUE  $\wedge$  ST_elevation(k1) = TRUE)
             $\wedge$ 
            (ST_seg_ele(l1)  $\geq$  1000  $\wedge$  ST_seg_ele(k1)  $\geq$  1000)
             $\wedge$  l1  $\neq$  k1
             $\wedge$ 
            (
                (l1 = V1  $\wedge$  k1 = V2)  $\vee$ 
                (l1 = V2  $\wedge$  k1 = V3)  $\vee$ 
                (l1 = V3  $\wedge$  k1 = V4)  $\vee$ 
                (l1 = V4  $\wedge$  k1 = V5)  $\vee$ 
                (l1 = V5  $\wedge$  k1 = V6)
            )
            ))
        grd4 : Disease_step4  $\in$  {Acute_inferior_MI, Acute_anterior_MI}
    then
        act1 : Disease_step4 := STEMI
    end

Event ST_seg_elevation_NO  $\hat{=}$ 
    ST segment No...

refines ST_seg_elevation_No

    when
        grd1 : Heart_State = KO
        grd2 : Sinus = Yes

```

```

    grd3 :  $\vee$ 
    ( $\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$ 
    ( $ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000$ ))
grd4 :  $\exists l, k \cdot l \in LEADS \wedge k \in LEADS \wedge$ 
    ( $ST\_depression(l) \geq 1000 \wedge ST\_depression(k) \geq 1000$ )
     $\wedge l \neq k$ 
then
    act1 :  $Disease\_step4 \in \{Troponin, CK\_MB, Ischemia, Non\_STEMI\}$ 
end

Event Acute_IA_MI  $\hat{=}$ 
    Inferior Anterior MI

refines ST_seg_elevation_Yes

when
    grd1 :  $Heart\_State = KO$ 
    grd2 :  $Sinus = Yes$ 
    grd3 :  $\vee$ 
    ( $(\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
    ( $ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE$ )
     $\wedge$ 
    ( $ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000$ )
     $\wedge l1 \neq k1$ 
     $\wedge$ 
    (
    ( $l1 = V1 \wedge k1 = V2$ )  $\vee$ 
    ( $l1 = V2 \wedge k1 = V3$ )  $\vee$ 
    ( $l1 = V3 \wedge k1 = V4$ )  $\vee$ 
    ( $l1 = V4 \wedge k1 = V5$ )  $\vee$ 
    ( $l1 = V5 \wedge k1 = V6$ )
    )
    ))
then
    act1 :  $Disease\_step4 \in \{Acute\_inferior\_MI, Acute\_anterior\_MI\}$ 
end

END

```

An Event-B Specification of Step4_ST_MI_Ref2
Generated Date: 25 Nov 2010 @ 03:39:16 PM

MACHINE Step4_ST_MI_Ref2

REFINES Step4_ST_MI_Ref

SEES Leads_ctx, Disease_Codes_ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
PP_Interval
RR_Interval
Small_R_QS A small R or QS wave in V1 and V2
Slurred_S_duration Slurred S duration
Delta_Wave Delta Wave
Disease_step3
ST_elevation ST segment elevation (Coved or Saddle-back)
Epsilon_Wave Epsilon Wave or (a terminal notch in the QRS)
ST_seg_ele ST segment for elevation 1mm=0.1mV
Disease_step4
ST_depression

INVARIANTS

inv1: $Sinus = Yes \wedge Disease_step4 \in \{Troponin, CK_MB\} \Rightarrow Heart_State = KO$
inv2: $Sinus = Yes \wedge Disease_step4 = Non_STEMI \Rightarrow Heart_State = KO$
inv3: $Sinus = Yes \wedge Disease_step4 = Ischemia \Rightarrow Heart_State = KO$

EVENTS

Initialisation

extended

begin

act1: $RR_Int_equidistant : \in LEADS \rightarrow BOOL$
act2: $PP_Int_equidistant : \in LEADS \rightarrow BOOL$
act3: $P_Positive : \in LEADS \rightarrow BOOL$
act4: $Sinus := No$
act5: $PP_Interval : \in LEADS \rightarrow \mathbb{N}$

```

act6 : RR.Interval :∈ LEADS → ℕ
act7 : Heart_Rate :∈ 1 .. 300
act8 : Heart_State := KO
act9 : PR.Int := 120
act10 : Disease_step2 := NDS2
act11 : QRS_Int := 50
act12 : Notched_R :∈ LEADS → BOOL
act13 : Small_R_QS :∈ LEADS → BOOL
act14 : Slurred_S_duration :∈ LEADS → ℕ1
act15 : M.Shape_Complex :∈ LEADS → BOOL
act16 : Slurred_S :∈ LEADS → BOOL
act17 : ST_elevation :∈ LEADS → BOOL
act18 : Epsilon_Wave :∈ LEADS → BOOL
act19 : Delta_Wave := 0
act20 : Disease_step3 := NDS3
act21 : ST_seg_ele :∈ LEADS → ℕ
act22 : Disease_step4 := NDS4
act57 : ST_depression :∈ LEADS → ℕ

end

Event Rhythm_test.TRUE ≐
  Sinus Rhythm with Normal Rate

extends Rhythm_test.TRUE

any
  rate
where
  grd1 : (∃ l. l ∈ {II, V1, V2} ∧ PP.Int.equidistant(l) = TRUE ∧
    RR.Int.equidistant(l) = TRUE ∧
    RR.Interval(l) = PP.Interval(l))
    ∧
    P.Positive(II) = TRUE
  grd4 : rate ∈ 60 .. 100
    60..100 is the range of normal heart rate
  grd5 : PR.Int ≤ 200
    Heart is Normal if PR ≤ 200 QRS_Int < 120
    HeartisNormalifQRS < 120
  grd6
  grd7 : Disease_step2 = NDS2
  grd8 : Disease_step3 = NDS3
  grd9 : Disease_step4 = NDS4
then
  act1 : Sinus := Yes
  act2 : Heart_Rate := rate
  act3 : Heart_State := OK
end

Event Rhythm_test.FALSE ≐
  Abnormal Rhythm with Rate

extends Rhythm_test.FALSE

any

```

```

    rate
  where
    grd1 : ( $\forall l. l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \vee$ 
      RR_Int_equidistant(l) = FALSE  $\vee$ 
      RR_Interval(l)  $\neq$  PP_Interval(l))
       $\vee$ 
      P_Positive(II) = FALSE
    grd2 : rate  $\in$  1 .. 300
  then
    act1 : Sinus := No
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end

Event Rhythm_test.TRUE.Rate  $\hat{=}$ 
  Sinus Rhythm with abnormal Rate

extends Rhythm_test.TRUE.Rate

  any
    rate
  where
    grd1 : ( $\exists l. l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
      RR_Int_equidistant(l) = TRUE  $\wedge$ 
      RR_Interval(l) = PP_Interval(l))
       $\wedge$ 
      P_Positive(II) = TRUE
    grd5 : rate  $\in$  1 .. 300  $\setminus$  60 .. 100
      60..100 is the range of normal heart rate, so rest of no. is abnormal
    grd6 : Disease_step3 = WPW_Syndrome  $\vee$  Disease_step3 = Brugada_Syndrome  $\vee$ 
      Disease_step3 = RV_Dysplasia  $\vee$  Disease_step3 = IVCD
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end

Event PR_Test  $\hat{=}$ 
  PR Interval Test

extends PR_Test

  any
    pr
  where
    grd1 : pr  $\in$  120 .. 220
      time interval in (ms.)
    grd2 : pr > 200
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
  then
    act1 : PR_Int := pr
    act2 : Disease_step2 := First_degree_AV_Block

```

```

    end

Event QRS_Test_LBBB  $\hat{=}$ 
    QRS Complex Interval Test

extends QRS_Test_LBBB

any
    qrs
where
    grd1 : qrs  $\in$  50 .. 150
    grd2 : qrs  $\geq$  120
    grd3 : Sinus = Yes
    grd4 : Heart.State = KO
    grd5 : Notched_R(I) = TRUE  $\wedge$ 
        Notched_R(V5) = TRUE  $\wedge$ 
        Notched_R(V6) = TRUE
        Right Bundle Branch Block (RBBB)
    grd6 : Small_R_QS(V1) = TRUE  $\wedge$ 
        Small_R_QS(V2) = TRUE

then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := LBBB
end

Event QRS_Test_RBBB  $\hat{=}$ 
    Right Bundle Branch Block (RBBB)

extends QRS_Test_RBBB

any
    qrs
where
    grd1 : qrs  $\in$  50 .. 150
    grd2 : qrs  $\geq$  120
    grd3 : Sinus = Yes
    grd4 : Heart.State = KO
    grd5 : M.Shape_Complex(V1) = TRUE  $\wedge$ 
        M.Shape_Complex(V2) = TRUE
    grd7 : Slurred_S(I) = TRUE  $\wedge$ 
        Slurred_S(V5) = TRUE  $\wedge$ 
        Slurred_S(V6) = TRUE
    grd8 : Slurred_S_duration(I) > 40  $\wedge$ 
        Slurred_S_duration(V5) > 40  $\wedge$ 
        Slurred_S_duration(V6) > 40

then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := RBBB
end

Event QRS_Test_Atypical_RLBBB-WPW_Syndrome  $\hat{=}$ 
    QRS Test for Atypical LBBB RBBB

extends QRS_Test_Atypical_RLBBB-WPW_Syndrome

```

```

any
  sympt
  d_wave
where
  grd1 : QRS_Int ≥ 110
  grd2 : sympt = A_RBBB ∨ sympt = A_LBBB
  grd3 : d_wave ∈ ℕ
  grd4 : (d_wave + PR_Int) ≤ 120
  Delta_Wave + PR ≤ 120 Heart_State = KO
then
  act2 : Delta_Wave := d_wave
  act3 : Disease_step3 := WPW_Syndrome
end

Event QRS_Test_Atypical_RBBB_Brugada_Syndrome ≐
  Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends QRS_Test_Atypical_RBBB_Brugada_Syndrome

any
  sympt
  dis
where
  grd1 : sympt = A_RBBB
  grd2 : Heart_State = KO
  grd3 : QRS_Int ≥ 110
  grd4 : Slurred_S(V5) = FALSE ∧
    Slurred_S(V6) = FALSE
  grd5 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, NDS3}
  grd6 : ST_elevation(V1) = TRUE ∧
    ST_elevation(V2) = TRUE
  grd7 : Sinus = Yes
then
  act1 : Disease_step3 := Brugada_Syndrome
end

Event QRS_Test_Atypical_RBBB_RV_Dysplasia ≐
  Right Ventricular Dysplasia

extends QRS_Test_Atypical_RBBB_RV_Dysplasia

any
  sympt
  dis
where
  grd1 : sympt = A_RBBB
  grd2 : Heart_State = KO
  grd3 : QRS_Int ≥ 110
  grd4 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, NDS3}
  grd5 : Epsilon_Wave(V1) = TRUE ∧
    Epsilon_Wave(V3) = TRUE
then

```



```

        act1 : Disease_step3 := RV_Dysplasia
    end
Event QRS_Test_Atypical_RBBB_IVCD  $\hat{=}$ 
    IVCD diagnosis
extends QRS_Test_Atypical_RBBB_IVCD
    any
        dis
    where
        grd1 : QRS_Int  $\geq$  110
        grd2 : dis  $\in$  Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, NDS3}
        grd3 : Heart_State = KO
    then
        act1 : Disease_step3 := IVCD
    end
Event ST_seg_elevation_YES  $\hat{=}$ 
    ST segment elevation...
refines ST_seg_elevation_YES
    when
        grd1 : Heart_State = KO
        grd2 : Sinus = Yes
        grd3 :
             $\vee$ 
            (( $\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
            (ST_elevation(l1) = TRUE  $\wedge$  ST_elevation(k1) = TRUE)
             $\wedge$ 
            (ST_seg_ele(l1)  $\geq$  1000  $\wedge$  ST_seg_ele(k1)  $\geq$  1000)
             $\wedge$  l1  $\neq$  k1
             $\wedge$ 
            (
            (l1 = V1  $\wedge$  k1 = V2)  $\vee$ 
            (l1 = V2  $\wedge$  k1 = V3)  $\vee$ 
            (l1 = V3  $\wedge$  k1 = V4)  $\vee$ 
            (l1 = V4  $\wedge$  k1 = V5)  $\vee$ 
            (l1 = V5  $\wedge$  k1 = V6)
            )
            ))
        grd4 : Disease_step4  $\in$  {Acute_inferior_MI, Acute_anterior_MI}
    then
        act1 : Disease_step4 := STEMI
    end
Event ST_seg_elevation_NOTCKMB_Yes  $\hat{=}$ 
    Troponin or CK-MB positive YES
refines ST_seg_elevation_NO
    when
        grd1 : Heart_State = KO
        grd2 : Sinus = Yes

```

```

    grd3 :  $\bigvee$ 
      ( $\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$ 
        ( $ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000$ ))
grd4 :  $\exists l, k \cdot l \in LEADS \wedge k \in LEADS \wedge$ 
      ( $ST\_depression(l) \geq 1000 \wedge ST\_depression(k) \geq 1000$ )
       $\wedge l \neq k$ 
grd5 :  $Disease\_step4 \in \{Troponin, CK\_MB\}$ 
  then
    act1 :  $Disease\_step4 := Non\_STEMI$ 
  end

Event  $ST\_seg\_elevation\_NO\_TCKMB\_No \hat{=}$ 
  Troponin or CK-MB positive No

refines  $ST\_seg\_elevation\_NO$ 
  when
    grd1 :  $Heart\_State = KO$ 
    grd2 :  $Sinus = Yes$ 
    grd3 :  $\bigvee$ 
      ( $\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$ 
        ( $ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000$ ))
grd4 :  $\exists l, k \cdot l \in LEADS \wedge k \in LEADS \wedge$ 
      ( $ST\_depression(l) \geq 1000 \wedge ST\_depression(k) \geq 1000$ )
       $\wedge l \neq k$ 
grd5 :  $Disease\_step4 \notin \{Troponin, CK\_MB\}$ 
  then
    act1 :  $Disease\_step4 := Ischemia$ 
  end

Event  $Acute\_IA\_MI \hat{=}$ 
  Inferior Anterior MI

refines  $Acute\_IA\_MI$ 
  when
    grd1 :  $Heart\_State = KO$ 
    grd2 :  $Sinus = Yes$ 
    grd3 :  $\bigvee$ 
      ( $(\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
        ( $ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE$ ))
       $\wedge$ 
        ( $ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000$ )
       $\wedge l1 \neq k1$ 
       $\wedge$ 
        (
          ( $l1 = V1 \wedge k1 = V2$ )  $\vee$ 
          ( $l1 = V2 \wedge k1 = V3$ )  $\vee$ 
          ( $l1 = V3 \wedge k1 = V4$ )  $\vee$ 
          ( $l1 = V4 \wedge k1 = V5$ )  $\vee$ 
          ( $l1 = V5 \wedge k1 = V6$ )
        )
      )
  )
  then
    act1 :  $Disease\_step4 \in \{Acute\_inferior\_MI, Acute\_anterior\_MI\}$ 
  end

```

END

CONTEXT Step5_ctx

SETS

Age_of_Infarct
Disease_Codes_Step5
Mice_State5

CONSTANTS

recent
indeterminate
old
Hypertrophic_cardiomyopathy
lateral_MI
anterior_MI
LVH
emphysema
NDS5
Exclude_Mimics_MI
late_transition
normal_variant
borderline_Qs
NMS

AXIOMS

axm1 : $Age_of_Infarct = \{recent, indeterminate, old\}$
axm2 : $\neg recent = indeterminate$
axm3 : $\neg recent = old$
axm4 : $\neg indeterminate = old$
axm5 : $Disease_Codes_Step5 = \{Hypertrophic_cardiomyopathy, lateral_MI, anterior_MI, LVH, emphysema, NDS5\}$
axm7 : $\neg Hypertrophic_cardiomyopathy = lateral_MI$
axm8 : $\neg Hypertrophic_cardiomyopathy = anterior_MI$
axm9 : $\neg Hypertrophic_cardiomyopathy = LVH$
axm11 : $\neg Hypertrophic_cardiomyopathy = emphysema$
axm12 : $\neg Hypertrophic_cardiomyopathy = NDS5$
axm19 : $\neg lateral_MI = anterior_MI$
axm20 : $\neg lateral_MI = LVH$
axm22 : $\neg lateral_MI = emphysema$
axm23 : $\neg lateral_MI = NDS5$
axm24 : $\neg anterior_MI = LVH$
axm26 : $\neg anterior_MI = emphysema$
axm27 : $\neg anterior_MI = NDS5$
axm29 : $\neg LVH = emphysema$

axm30 : $\neg LVH = NDS5$
axm33 : $\neg emphysema = NDS5$
axm34 : $Mice_State5 = \{Exclude_Mimics_MI, late_transition, normal_variant, borderline_Qs, NMS\}$

NMS No Mice. State

axm35 : $\neg Exclude_Mimics_MI = late_transition$
axm36 : $\neg Exclude_Mimics_MI = normal_variant$
axm37 : $\neg Exclude_Mimics_MI = borderline_Qs$
axm44 : $\neg Exclude_Mimics_MI = NMS$
axm38 : $\neg late_transition = normal_variant$
axm39 : $\neg late_transition = borderline_Qs$
axm43 : $\neg late_transition = NMS$
axm40 : $\neg normal_variant = borderline_Qs$
axm41 : $\neg normal_variant = NMS$
axm42 : $\neg borderline_Qs = NMS$

END

An Event-B Specification of Step5_Q_Waves
Generated Date: 25 Nov 2010 @ 03:39:19 PM

MACHINE Step5_Q_Waves

REFINES Step4_ST_MI_Ref2

SEES Leads_ctx, Disease_Codes_ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
Small_R_QS A small R or QS wave in V1 and V2
PP_Interval
RR_Interval
Slurred_S_duration Slurred S duration
Delta_Wave Delta Wave
Disease_step3
ST_elevation ST segment elevation (Coved or Saddle-back)
Epsilon_Wave Epsilon Wave or (a terminal notch in the QRS)
ST_seg_ele ST segment for elevation 1mm=0.1mV
Disease_step4
Q_Width Q wave width
Q_Depth Q wave depth
Q_Normal_Status Q wave normal or abnormal
ST_depression

INVARIANTS

inv1: $Q_Width \in LEADS \rightarrow \mathbb{N}$
inv2: $Q_Depth \in LEADS \rightarrow \mathbb{N}$
inv3: $Q_Normal_Status \in \text{BOOL}$
inv4: $Sinus = \text{Yes} \wedge Disease_step4 = \text{Acute_anterior_MI} \Rightarrow Heart_State = \text{KO}$
inv5: $Sinus = \text{Yes} \wedge Disease_step4 = \text{Acute_inferior_MI} \Rightarrow Heart_State = \text{KO}$

EVENTS

Initialisation

extended

begin

```
act1 : RR_Int_equidistant :∈ LEADS → BOOL
act2 : PP_Int_equidistant :∈ LEADS → BOOL
act3 : P_Positive :∈ LEADS → BOOL
act4 : Sinus := No
act5 : PP_Interval :∈ LEADS → ℕ
act6 : RR_Interval :∈ LEADS → ℕ
act7 : Heart_Rate :∈ 1 .. 300
act8 : Heart_State := KO
act9 : PR_Int := 120
act10 : Disease_step2 := NDS2
act11 : QRS_Int := 50
act12 : Notched_R :∈ LEADS → BOOL
act13 : Small_R_QS :∈ LEADS → BOOL
act14 : Slurred_S_duration :∈ LEADS → ℕ1
act15 : M_Shape_Complex :∈ LEADS → BOOL
act16 : Slurred_S :∈ LEADS → BOOL
act17 : ST_elevation :∈ LEADS → BOOL
act18 : Epsilon_Wave :∈ LEADS → BOOL
act19 : Delta_Wave := 0
act20 : Disease_step3 := NDS3
act21 : ST_seg_ele :∈ LEADS → ℕ
act22 : Disease_step4 := NDS4
act57 : ST_depression :∈ LEADS → ℕ
act23 : Q_Width :∈ LEADS → ℕ
act24 : Q_Depth :∈ LEADS → ℕ
act25 : Q_Normal_Status := FALSE
```

end

Event *Rhythm_test.TRUE* $\hat{=}$

Sinus Rhythm with Normal Rate

extends *Rhythm_test.TRUE*

any

rate

where

```
grd1 : (∃ l. l ∈ {II, V1, V2} ∧ PP_Int_equidistant(l) = TRUE ∧
        RR_Int_equidistant(l) = TRUE ∧
        RR_Interval(l) = PP_Interval(l))
        ∧
        P_Positive(II) = TRUE
grd4 : rate ∈ 60 .. 100
        60..100 is the range of normal heart rate
grd5 : PR_Int ≤ 200
        Heart is Normal if PR ≤ 200 QRS_Int < 120
        Heart is Normal if QRS < 120
grd6 : Disease_step2 = NDS2
grd7 : Disease_step3 = NDS3
```

```

    grd9 : Disease_step4 = NDS4
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := OK
  end
Event Rhythm_test_FALSE  $\hat{=}$ 
  Abnormal Rhythm with Rate
extends Rhythm_test_FALSE
  any
    rate
  where
    grd1 : ( $\forall 1 \cdot 1 \in \{II, V1, V2\} \Rightarrow$  PP_Int_equidistant(1) = FALSE  $\vee$ 
      RR_Int_equidistant(1) = FALSE  $\vee$ 
      RR.Interval(1)  $\neq$  PP.Interval(1))
       $\vee$ 
      P_Positive(II) = FALSE
    grd2 : rate  $\in$  1 .. 300
  then
    act1 : Sinus := No
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end
Event Rhythm_test_TRUE_Rate  $\hat{=}$ 
  Sinus Rhythm with abnormal Rate
extends Rhythm_test_TRUE_Rate
  any
    rate
  where
    grd1 : ( $\exists 1 \cdot 1 \in \{II, V1, V2\} \wedge$  PP_Int_equidistant(1) = TRUE  $\wedge$ 
      RR_Int_equidistant(1) = TRUE  $\wedge$ 
      RR.Interval(1) = PP.Interval(1))
       $\wedge$ 
      P_Positive(II) = TRUE
    grd5 : rate  $\in$  1 .. 300  $\setminus$  60 .. 100
      60..100 is the range of normal heart rate, so rest of no. is abnormal
    grd6 : Disease_step3 = WPW.Syndrome  $\vee$  Disease_step3 = Brugada.Syndrome  $\vee$ 
      Disease_step3 = RV_Dysplasia  $\vee$  Disease_step3 = IVCD
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end
Event PR_Test  $\hat{=}$ 
  PR Interval Test
extends PR_Test

```

```

any
  pr
where
  grd1 : pr ∈ 120 .. 220
         time interval in (ms.)
  grd2 : pr > 200
  grd3 : Sinus = Yes
  grd4 : Heart_State = KO
then
  act1 : PR_Int := pr
  act2 : Disease_step2 := First_degree_AV_Block
end

Event QRS_Test_LBBB ≐
QRS Complex Interval Test

extends QRS_Test_LBBB

any
  qrs
where
  grd1 : qrs ∈ 50 .. 150
  grd2 : qrs ≥ 120
  grd3 : Sinus = Yes
  grd4 : Heart_State = KO
  grd5 : Notched_R(I) = TRUE ∧
         Notched_R(V5) = TRUE ∧
         Notched_R(V6) = TRUE
         Right Bundle Branch Block (RBBB)
  grd6 : Small_R_QS(V1) = TRUE ∧
         Small_R_QS(V2) = TRUE
then
  act1 : QRS_Int := qrs
  act2 : Disease_step2 := LBBB
end

Event QRS_Test_RBBB ≐
Right Bundle Branch Block (RBBB)

extends QRS_Test_RBBB

any
  qrs
where
  grd1 : qrs ∈ 50 .. 150
  grd2 : qrs ≥ 120
  grd3 : Sinus = Yes
  grd4 : Heart_State = KO
  grd5 : M.Shape_Complex(V1) = TRUE ∧
         M.Shape_Complex(V2) = TRUE
  grd7 : Slurred_S(I) = TRUE ∧
         Slurred_S(V5) = TRUE ∧
         Slurred_S(V6) = TRUE

```



```

    grd8 : Slurred_S_duration(I) > 40 ∧
           Slurred_S_duration(V5) > 40 ∧
           Slurred_S_duration(V6) > 40
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := RBBB
  end

Event QRS_Test_Atypical_RLBBB_WPW_Syndrome ≐
  QRS Test for Atypical LBBB RBBB

extends QRS_Test_Atypical_RLBBB_WPW_Syndrome

  any
    sympt
    d_wave
  where
    grd1 : QRS_Int ≥ 110
    grd2 : sympt = A_RBBB ∨ sympt = A_LBBB
    grd3 : d_wave ∈ ℕ
    grd4 : (d_wave + PR_Int) ≤ 120
           Delta_Wave + PR ≤ 120 Heart_State = KO
  then
    act2 : Delta_Wave := d_wave
    act3 : Disease_step3 := WPW_Syndrome
  end

Event QRS_Test_Atypical_RBBB_Brugada_Syndrome ≐
  Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends QRS_Test_Atypical_RBBB_Brugada_Syndrome

  any
    sympt
    dis
  where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int ≥ 110
    grd4 : Slurred_S(V5) = FALSE ∧
           Slurred_S(V6) = FALSE
    grd5 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, NDS3}
    grd6 : ST_elevation(V1) = TRUE ∧
           ST_elevation(V2) = TRUE
    grd7 : Sinus = Yes
  then
    act1 : Disease_step3 := Brugada_Syndrome
  end

Event QRS_Test_Atypical_RBBB_RV_Dysplasia ≐
  Right Ventricular Dysplasia

extends QRS_Test_Atypical_RBBB_RV_Dysplasia

```

```

any
  sympt
  dis
where
  grd1 : sympt = A_RBBB
  grd2 : Heart_State = KO
  grd3 : QRS_Int ≥ 110
  grd4 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, NDS3}
  grd5 : Epsilon_Wave(V1) = TRUE ∧
        Epsilon_Wave(V3) = TRUE
then
  act1 : Disease_step3 := RV_Dysplasia
end

Event QRS_Test_Atypical_RBBB_IVCD ≐
  IVCD diagnosis

extends QRS_Test_Atypical_RBBB_IVCD

any
  dis
where
  grd1 : QRS_Int ≥ 110
  grd2 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, NDS3}
  grd3 : Heart_State = KO
then
  act1 : Disease_step3 := IVCD
end

Event ST_seg_elevation_YES ≐
  ST segment elevation...

refines ST_seg_elevation_YES

when
  grd1 : Heart_State = KO
  grd2 : Sinus = Yes
  grd3 :
    ∨
    ((∃ l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
    (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
    ∧
    (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
    ∧ l1 ≠ k1
    ∧
    (
    (l1 = V1 ∧ k1 = V2) ∨
    (l1 = V2 ∧ k1 = V3) ∨
    (l1 = V3 ∧ k1 = V4) ∨
    (l1 = V4 ∧ k1 = V5) ∨
    (l1 = V5 ∧ k1 = V6)
    )
    )
grd4 : Disease_step4 ∈ {Acute_inferior_MI, Acute_anterior_MI}

```

```

then
  act1 : Disease_step4 := STEMI
end

Event ST_seg_elevation_NOTCKMB_Yes  $\hat{=}$ 
  Troponin or CK-MB positive YES

extends ST_seg_elevation_NOTCKMB_Yes

when
  grd1 : Heart_State = KO
  grd2 : Sinus = Yes
  grd3 :  $\bigvee$ 
    ( $\forall l \cdot l \in \{II, III, aVF\} \Rightarrow$ 
    (ST_elevation(l) = FALSE  $\wedge$  ST_seg_ele(l) < 1000))
grd4 :  $\exists l, k \cdot l \in \text{LEADS} \wedge k \in \text{LEADS} \wedge$ 
    (ST_depression(l)  $\geq$  1000  $\wedge$  ST_depression(k)  $\geq$  1000)
     $\wedge l \neq k$ 
grd5 : Disease_step4  $\in$  {Troponin, CK_MB}

then
  act1 : Disease_step4 := Non-STEMI
end

Event ST_seg_elevation_NO_TCKMB_No  $\hat{=}$ 
  Troponin or CK-MB positive No

extends ST_seg_elevation_NO_TCKMB_No

when
  grd1 : Heart_State = KO
  grd2 : Sinus = Yes
  grd3 :  $\bigvee$ 
    ( $\forall l \cdot l \in \{II, III, aVF\} \Rightarrow$ 
    (ST_elevation(l) = FALSE  $\wedge$  ST_seg_ele(l) < 1000))
grd4 :  $\exists l, k \cdot l \in \text{LEADS} \wedge k \in \text{LEADS} \wedge$ 
    (ST_depression(l)  $\geq$  1000  $\wedge$  ST_depression(k)  $\geq$  1000)
     $\wedge l \neq k$ 
grd5 : Disease_step4  $\notin$  {Troponin, CK_MB}

then
  act1 : Disease_step4 := Ischemia
end

Event Q_Assessment_Normal  $\hat{=}$ 
  Q wave assessment normal

when
  grd1 : Q_Width(II) < 40  $\wedge$  Q_Depth(II)  $\leq$  3000  $\wedge$ 
    Q_Width(aVF) < 40  $\wedge$  Q_Depth(aVF)  $\leq$  3000  $\wedge$ 
    Q_Width(aVL) < 40
    1000 micrometer = 1 millimeter
  grd2 : Q_Width(III)  $\leq$  40  $\wedge$  Q_Depth(III)  $\leq$  7000  $\wedge$  Q_Depth(aVL)  $\leq$  7000
  grd3 : Q_Depth(I) < 40  $\wedge$  Q_Depth(I)  $\leq$  1500

then
  act1 : Q_Normal_Status := TRUE

```

```

end

Event Q_Assessment_Abnormal_AMI  $\hat{=}$ 
  Q wave assessment abnormal for anterolateral MI (AMI)

refines Acute_IA_MI

when
  grd1 : Heart_State = KO
  grd2 : Sinus = Yes
  grd3 :  $\vee$ 
    (( $\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
    (ST_elevation(l1) = TRUE  $\wedge$  ST_elevation(k1) = TRUE)
     $\wedge$ 
    (ST_seg_ele(l1)  $\geq$  1000  $\wedge$  ST_seg_ele(k1)  $\geq$  1000)
     $\wedge$  l1  $\neq$  k1
     $\wedge$ 
    (
    (l1 = V1  $\wedge$  k1 = V2)  $\vee$ 
    (l1 = V2  $\wedge$  k1 = V3)  $\vee$ 
    (l1 = V3  $\wedge$  k1 = V4)  $\vee$ 
    (l1 = V4  $\wedge$  k1 = V5)  $\vee$ 
    (l1 = V5  $\wedge$  k1 = V6)
    )
    ))
  grd4 : Q_Width(V5)  $\geq$  40  $\wedge$  Q_Depth(V5) > 3000  $\wedge$ 
    Q_Width(V6)  $\geq$  40  $\wedge$  Q_Depth(V6) > 3000
  grd5 : Q_Width(aVL)  $\geq$  40  $\wedge$  Q_Depth(aVL) > 7000
  grd6 : Q_Depth(I)  $\geq$  40  $\wedge$  Q_Depth(I) > 1500
  grd7 : Q_Normal_Status = FALSE
  then
    act1 : Disease_step4 := Acute_anterior_MI
  end

Event Q_Assessment_Abnormal_IMI  $\hat{=}$ 
  Q wave assessment abnormal for inferior MI (IMI)

refines Acute_IA_MI

when
  grd1 : Heart_State = KO
  grd2 : Sinus = Yes
  grd3 :  $\vee$ 
    (( $\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
    (ST_elevation(l1) = TRUE  $\wedge$  ST_elevation(k1) = TRUE)
     $\wedge$ 
    (ST_seg_ele(l1)  $\geq$  1000  $\wedge$  ST_seg_ele(k1)  $\geq$  1000)
     $\wedge$  l1  $\neq$  k1
     $\wedge$ 
    (
    (l1 = V1  $\wedge$  k1 = V2)  $\vee$ 
    (l1 = V2  $\wedge$  k1 = V3)  $\vee$ 
    (l1 = V3  $\wedge$  k1 = V4)  $\vee$ 
    (l1 = V4  $\wedge$  k1 = V5)  $\vee$ 
    (l1 = V5  $\wedge$  k1 = V6)
    )
    ))

```

```
grd4:  $Q\_Width(II) \geq 40 \wedge Q\_Depth(II) > 3000 \wedge$   
       $Q\_Width(III) > 40 \wedge Q\_Depth(III) > 7000 \wedge$   
       $Q\_Width(aVF) \geq 40 \wedge Q\_Depth(aVF) > 3000$   
grd5:  $Q\_Normal\_Status = FALSE$   
      then  
        act1:  $Disease\_step4 := Acute\_inferior\_MI$   
      end  
END
```

An Event-B Specification of Step5.Q.Waves_Ref1
Generated Date: 25 Nov 2010 @ 03:39:22 PM

MACHINE Step5.Q.Waves_Ref1

REFINES Step5.Q.Waves

SEES Leads.ctx, Disease_Codes.ctx, Step5.ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
Small_R_QS A small R or QS wave in V1 and V2
Slurred_S_duration Slurred S duration
Delta_Wave Delta Wave
Disease_step3
ST_elevation ST segment elevation (Coved or Saddle-back)
PP_Interval
RR_Interval
Epsilon_Wave Epsilon Wave or (a terminal notch in the QRS)
ST_seg_ele ST segment for elevation 1mm=0.1mV
Disease_step4
Q_Width Q wave width
Q_Depth Q wave depth
Q_Normal_Status Q wave normal or abnormal
Age_of_Inf Age of Infarct
Disease_step5
Mice_State
R_Depth R wave depth or height
R_Normal_Status R wave normal or abnormal
Q_Wave_State Q wave states for all LEADS
ST_depression

INVARIANTS

inv1 : $Age_of_Inf \in Age_of_Infarct$
inv2 : $Disease_step5 \in Disease_Codes_Step5$
inv3 : $Mice_State \in Mice_State5$

inv4 : $R_Depth \in LEADS \rightarrow \mathbb{N}$
inv5 : $R_Normal_Status \in BOOL$
inv6 : $Q_Wave_State \in LEADS \rightarrow BOOL$
inv7 : $Sinus = Yes \wedge Disease_step5 = Hypertrophic_cardiomyopathy \Rightarrow Heart_State = KO$
inv8 : $Sinus = Yes \wedge Disease_step5 \in \{anterior_MI, LVH, emphysema, lateral_MI\} \Rightarrow Heart_State = KO$

EVENTS

Initialisation

extended

begin

act1 : $RR_Int_equidistant \in LEADS \rightarrow BOOL$
act2 : $PP_Int_equidistant \in LEADS \rightarrow BOOL$
act3 : $P_Positive \in LEADS \rightarrow BOOL$
act4 : $Sinus := No$
act5 : $PP_Interval \in LEADS \rightarrow \mathbb{N}$
act6 : $RR_Interval \in LEADS \rightarrow \mathbb{N}$
act7 : $Heart_Rate \in 1..300$
act8 : $Heart_State := KO$
act9 : $PR_Int := 120$
act10 : $Disease_step2 := NDS2$
act11 : $QRS_Int := 50$
act12 : $Notched_R \in LEADS \rightarrow BOOL$
act13 : $Small_R_QS \in LEADS \rightarrow BOOL$
act14 : $Slurred_S_duration \in LEADS \rightarrow \mathbb{N}_1$
act15 : $M_Shape_Complex \in LEADS \rightarrow BOOL$
act16 : $Slurred_S \in LEADS \rightarrow BOOL$
act17 : $ST_elevation \in LEADS \rightarrow BOOL$
act18 : $Epsilon_Wave \in LEADS \rightarrow BOOL$
act19 : $Delta_Wave := 0$
act20 : $Disease_step3 := NDS3$
act21 : $ST_seg_ele \in LEADS \rightarrow \mathbb{N}$
act22 : $Disease_step4 := NDS4$
act57 : $ST_depression \in LEADS \rightarrow \mathbb{N}$
act23 : $Q_Width \in LEADS \rightarrow \mathbb{N}$
act24 : $Q_Depth \in LEADS \rightarrow \mathbb{N}$
act25 : $Q_Normal_Status := FALSE$
act26 : $Mice_State := NMS$
act27 : $R_Depth \in LEADS \rightarrow \mathbb{N}$
act28 : $R_Normal_Status := FALSE$
act29 : $Q_Wave_State \in LEADS \rightarrow BOOL$
act30 : $Age_of_Inf \in Age_of_Infarct$
act31 : $Disease_step5 := NDS5$

end

Event $Rhythm_test_TRUE \hat{=}$
 Sinus Rhythm with Normal Rate

extends $Rhythm_test_TRUE$

any

```

    rate
  where
    grd1 : ( $\exists l. l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
      RR_Int_equidistant(l) = TRUE  $\wedge$ 
      RR_Interval(l) = PP_Interval(l))
       $\wedge$ 
      P_Positive(II) = TRUE
    grd4 : rate  $\in$  60 .. 100
      60..100 is the range of normal heart rate
    grd5 : PR_Int  $\leq$  200
      Heart is Normal if PR  $\leq$  200 QRS_Int < 120
      Heart is Normal if QRS < 120
    grd7 : Disease_step2 = NDS2
    grd8 : Disease_step3 = NDS3
    grd9 : Disease_step4 = NDS4
    grd10 : Disease_step5 = NDS5
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := OK
  end
Event Rhythm_test_FALSE  $\hat{=}$ 
  Abnormal Rhythm with Rate
extends Rhythm_test_FALSE
  any
    rate
  where
    grd1 : ( $\forall l. l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \vee$ 
      RR_Int_equidistant(l) = FALSE  $\vee$ 
      RR_Interval(l)  $\neq$  PP_Interval(l))
       $\vee$ 
      P_Positive(II) = FALSE
    grd2 : rate  $\in$  1 .. 300
  then
    act1 : Sinus := No
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end
Event Rhythm_test_TRUE_Rate  $\hat{=}$ 
  Sinus Rhythm with abnormal Rate
extends Rhythm_test_TRUE_Rate
  any
    rate
  where
    grd1 : ( $\exists l. l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
      RR_Int_equidistant(l) = TRUE  $\wedge$ 
      RR_Interval(l) = PP_Interval(l))
       $\wedge$ 
      P_Positive(II) = TRUE

```



```

    grd5 : rate ∈ 1..300 \ 60..100
           60..100 is the range of normal heart rate, so rest of no. is abnormal
    grd6 : Disease_step3 = WPW_Syndrome ∨ Disease_step3 = Brugada_Syndrome ∨
           Disease_step3 = RV_Dysplasia ∨ Disease_step3 = IVCD

  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end

Event PR_Test ≐
  PR Interval Test

extends PR_Test

  any
    pr
  where
    grd1 : pr ∈ 120..220
           time interval in (ms.)
    grd2 : pr > 200
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
  then
    act1 : PR_Int := pr
    act2 : Disease_step2 := First_degree_AV_Block
  end

Event QRS_Test_LBBB ≐
  QRS Complex Interval Test

refines QRS_Test_LBBB

  any
    qrs
  where
    grd1 : qrs ∈ 50..150
    grd2 : qrs ≥ 120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : Notched_R(I) = TRUE ∧
           Notched_R(V5) = TRUE ∧
           Notched_R(V6) = TRUE
           Right Bundle Branch Block (RBBB)
    grd6 : Small_R_QS(V1) = TRUE ∧
           Small_R_QS(V2) = TRUE
    grd7 : Q_Wave_State(V1) = TRUE ∧
           Q_Wave_State(V2) = TRUE ∧
           Q_Wave_State(V3) = TRUE ∧
           Q_Wave_State(V4) = TRUE
           from step 5
    grd8 : R_Normal_Status = FALSE
           from step 5

```

```

then
  act1 : QRS_Int := qrs
  act2 : Disease_step2 := LBBB
end

Event QRS_Test_RBBB  $\hat{=}$ 
  Right Bundle Branch Block (RBBB)

refines QRS_Test_RBBB

any
  qrs
where
  grd1 : qrs  $\in$  50 .. 150
  grd2 : qrs  $\geq$  120
  grd3 : Sinus = Yes
  grd4 : Heart_State = KO
  grd5 : M_Shape_Complex(V1) = TRUE  $\wedge$ 
    M_Shape_Complex(V2) = TRUE
  grd7 : Slurred_S(I) = TRUE  $\wedge$ 
    Slurred_S(V5) = TRUE  $\wedge$ 
    Slurred_S(V6) = TRUE
  grd8 : Slurred_S_duration(I) > 40  $\wedge$ 
    Slurred_S_duration(V5) > 40  $\wedge$ 
    Slurred_S_duration(V6) > 40

then
  act1 : QRS_Int := qrs
  act2 : Disease_step2 := RBBB
end

Event QRS_Test_Atypical_RLBBB_WPW_Syndrome  $\hat{=}$ 
  QRS Test for Atypical LBBB RBBB

refines QRS_Test_Atypical_RLBBB_WPW_Syndrome

any
  sympt
  d_wave
  exmi
where
  grd1 : QRS_Int  $\geq$  110
  grd2 : sympt = A_RBBB  $\vee$  sympt = A_LBBB
  grd3 : d_wave  $\in$   $\mathbb{N}$ 
  grd4 : (d_wave + PR_Int)  $\leq$  120
    Delta Wave + PR  $\leq$  120 Heart_State = KO
  grd5 : Disease_step4 = Acute_inferior_MI
  grd6 : Disease_step4 = Acute_inferior_MI
  grd7 : exmi  $\in$  Mice_State5  $\wedge$  exmi = Exclude_Mimics_MI

then
  act2 : Delta_Wave := d_wave
  act3 : Disease_step3 := WPW_Syndrome
end

```

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* $\hat{=}$
Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt
dis

where

grd1 : sympt = A_RBBB
grd2 : Heart_State = KO
grd3 : QRS_Int \geq 110
grd4 : Slurred_S(V5) = FALSE \wedge
Slurred_S(V6) = FALSE
grd5 : dis \in Disease_Codes_Step3 \ {WPW_Syndrome, NDS3}
grd6 : ST_elevation(V1) = TRUE \wedge
ST_elevation(V2) = TRUE
grd7 : Sinus = Yes

then

act1 : Disease_step3 := Brugada_Syndrome

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\hat{=}$
Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt
dis

where

grd1 : sympt = A_RBBB
grd2 : Heart_State = KO
grd3 : QRS_Int \geq 110
grd4 : dis \in Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, NDS3}
grd5 : Epsilon_Wave(V1) = TRUE \wedge
Epsilon_Wave(V3) = TRUE

then

act1 : Disease_step3 := RV_Dysplasia

end

Event *QRS_Test_Atypical_RBBB_IVCD* $\hat{=}$
IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

dis

where

grd1 : QRS_Int \geq 110
grd2 : dis \in Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, NDS3}
grd3 : Heart_State = KO

then

```

        act1 : Disease_step3 := IVCD
    end

Event ST_seg_elevation_YES  $\hat{=}$ 
    ST segment elevation...

extends ST_seg_elevation_YES

    when
        grd1 : Heart.State = KO
        grd2 : Sinus = Yes
        grd3 :  $\vee$ 
            (( $\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
            (ST_elevation(l1) = TRUE  $\wedge$  ST_elevation(k1) = TRUE)
             $\wedge$ 
            (ST_seg_ele(l1)  $\geq$  1000  $\wedge$  ST_seg_ele(k1)  $\geq$  1000)
             $\wedge$  l1  $\neq$  k1
             $\wedge$ 
            (
            (l1 = V1  $\wedge$  k1 = V2)  $\vee$ 
            (l1 = V2  $\wedge$  k1 = V3)  $\vee$ 
            (l1 = V3  $\wedge$  k1 = V4)  $\vee$ 
            (l1 = V4  $\wedge$  k1 = V5)  $\vee$ 
            (l1 = V5  $\wedge$  k1 = V6)
            )
            ))
        grd4 : Disease_step4  $\in$  {Acute_inferior_MI, Acute_anterior_MI}

    then
        act1 : Disease_step4 := STEMI
    end

Event ST_seg_elevation_NOTCKMB_Yes  $\hat{=}$ 
    Troponin or CK-MB positive YES

extends ST_seg_elevation_NOTCKMB_Yes

    when
        grd1 : Heart.State = KO
        grd2 : Sinus = Yes
        grd3 :  $\vee$ 
            ( $\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$ 
            (ST_elevation(l1) = FALSE  $\wedge$  ST_seg_ele(l1) < 1000))
        grd4 :  $\exists l, k \cdot l \in \text{LEADS} \wedge k \in \text{LEADS} \wedge$ 
            (ST_depression(l)  $\geq$  1000  $\wedge$  ST_depression(k)  $\geq$  1000)
             $\wedge$  l  $\neq$  k
        grd5 : Disease_step4  $\in$  {Troponin, CK_MB}

    then
        act1 : Disease_step4 := Non_STEMI
    end

Event ST_seg_elevation_NO_TCKMB_No  $\hat{=}$ 
    Troponin or CK-MB positive No

extends ST_seg_elevation_NO_TCKMB_No

    when

```

```

    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :
        ∨
        (∀l1·l1 ∈ {II, III, aVF} ⇒
        (ST_elevation(l1) = FALSE ∧ ST_seg_ele(l1) < 1000))
grd4 : ∃l, k·l ∈ LEADS ∧ k ∈ LEADS ∧
        (ST_depression(l) ≥ 1000 ∧ ST_depression(k) ≥ 1000
        ∧ l ≠ k)
grd5 : Disease_step4 ∉ {Troponin, CK_MB}
    then
        act1 : Disease_step4 := Ischemia
    end

Event Q_Assessment_Normal ≐
    Q wave assessment normal

extends Q_Assessment_Normal

when
    grd1 : Q_Width(II) < 40 ∧ Q_Depth(II) ≤ 3000 ∧
        Q_Width(aVF) < 40 ∧ Q_Depth(aVF) ≤ 3000 ∧
        Q_Width(aVL) < 40
        1000 micrometer = 1 millimeter
    grd2 : Q_Width(III) ≤ 40 ∧ Q_Depth(III) ≤ 7000 ∧ Q_Depth(aVL) ≤ 7000
    grd3 : Q_Depth(I) < 40 ∧ Q_Depth(I) ≤ 1500
then
    act1 : Q_Normal_Status := TRUE
end

Event Q_Assessment_Abnormal_AMI ≐
    Q wave assessment abnormal for anterolateral MI (AMI)

extends Q_Assessment_Abnormal_AMI

when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :
        ∨
        ((∃l1, k1·l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
        (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
        ∧
        (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
        ∧ l1 ≠ k1
        ∧
        (
        (l1 = V1 ∧ k1 = V2) ∨
        (l1 = V2 ∧ k1 = V3) ∨
        (l1 = V3 ∧ k1 = V4) ∨
        (l1 = V4 ∧ k1 = V5) ∨
        (l1 = V5 ∧ k1 = V6)
        )
        ))
grd4 : Q_Width(V5) ≥ 40 ∧ Q_Depth(V5) > 3000 ∧
        Q_Width(V6) ≥ 40 ∧ Q_Depth(V6) > 3000
grd5 : Q_Width(aVL) ≥ 40 ∧ Q_Depth(aVL) > 7000

```

```

grd6 : Q_Depth(I) ≥ 40 ∧ Q_Depth(I) > 1500
grd7 : Q_Normal_Status = FALSE
  then
    act1 : Disease_step4 := Acute_anterior_MI
  end

Event Q_Assessment_Abnormal_IMI ≐
  Q_wave_assessment_abnormal_for_inferior_MI(IMI)

refines Q_Assessment_Abnormal_IMI
  when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :
      ∨
      ((∃l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
      (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
      ∧
      (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
      ∧ l1 ≠ k1
      ∧
      (
      (l1 = V1 ∧ k1 = V2) ∨
      (l1 = V2 ∧ k1 = V3) ∨
      (l1 = V3 ∧ k1 = V4) ∨
      (l1 = V4 ∧ k1 = V5) ∨
      (l1 = V5 ∧ k1 = V6)
      )
      ))
grd4 : Q_Width(II) ≥ 40 ∧ Q_Depth(II) > 3000 ∧
  Q_Width(III) > 40 ∧ Q_Depth(III) > 7000 ∧
  Q_Width(aVF) ≥ 40 ∧ Q_Depth(aVF) > 3000
grd5 : Q_Normal_Status = FALSE
  then
    act1 : Disease_step4 := Acute_inferior_MI
  end

Event Determine_Age_of_Infarct ≐

  when
    grd1 : Disease_step4 = Acute_inferior_MI
      ∨
      Disease_step5 ∈ {anterior_MI, LVH, emphysema}
      ∨
      Mice_State = Exclude_Mimics_MI
      ∨
      Disease_step2 = LBBB
  then
    act1 : Age_of_Inf := {recent, old, indeterminate}
  end

Event Exclude_Mimics ≐

  any
    exmi

```

```

where
  grd1 : Disease_step4 = Acute_inferior_MI
  grd2 : exmi ∈ Mice_State5 ∧ exmi = Exclude_Mimics_MI
then
  act1 : Disease_step5 := Hypertrophic_cardiomyopathy
  act2 : Mice_State := borderline_Qs
end
Event R_Assessment_Normal ≐
Q wave assessment normal
any
  age
where
  grd1 : R_Depth(V1) ≥ 0 ∧ R_Depth(V1) ≤ 6000 ∧ age > 30
    1000 micrometer = 1 millimeter
  grd2 : R_Depth(V2) > 200 ∧ R_Depth(V2) ≤ 12000
  grd3 : R_Depth(V2) ≥ 1000 ∧ R_Depth(V2) ≤ 24000
then
  act1 : R_Normal_Status := TRUE
end
Event R_Assessment_Abnormal ≐
when
  grd1 : R_Normal_Status = FALSE
then
  act1 : Mice_State := {late_transition, normal_variant}
end
Event R_Q_Assessment_R_Abnormal_V1234 ≐
R wave abnormal , pathologic Q waves consider in V1-V4
when
  grd1 : R_Normal_Status = FALSE
  grd2 : Q_Wave_State(V1) = TRUE ∧
    Q_Wave_State(V2) = TRUE ∧
    Q_Wave_State(V3) = TRUE ∧
    Q_Wave_State(V4) = TRUE
  grd3 : Heart_State = KO
then
  act1 : Disease_step5 := {anterior_MI, LVH, emphysema}
  act2 : Mice_State := Exclude_Mimics_MI
end
Event R_Q_Assessment_R_Abnormal_V56 ≐
R wave abnormal , pathologic Q waves consider in V5-V6
when
  grd1 : Q_Wave_State(V5) = TRUE ∧
    Q_Wave_State(V6) = TRUE
  grd3 : Heart_State = KO
then
  act1 : Disease_step5 := {lateral_MI, Hypertrophic_cardiomyopathy}
end
END

```

An Event-B Specification of Step6_ctx
Generated Date: 25 Nov 2010 @ 03:38:56 PM

CONTEXT Step6_ctx

SETS

Disease_Codes_Step6

CONSTANTS

RAE Right Atrial Enlargement
RVH
RV_strain
pulmonary_embolism
LAE Left Atrial Enlargement
mitral_stenosis
mitral_regurgitation
LV_failure
dilated_cardiomyopathy
LVH_cause
NDS6

AXIOMS

axm1 : $Disease_Codes_Step6 = \{RAE, RVH, RV_strain, pulmonary_embolism, LAE, mitral_stenosis, mitral_regurgitation, LV_failure, dilated_cardiomyopathy, LVH_cause, NDS6\}$
axm2 : $\neg RAE = RVH$
axm3 : $\neg RAE = RV_strain$
axm4 : $\neg RAE = pulmonary_embolism$
axm5 : $\neg RAE = LAE$
axm6 : $\neg RAE = mitral_stenosis$
axm7 : $\neg RAE = mitral_regurgitation$
axm8 : $\neg RAE = LV_failure$
axm9 : $\neg RAE = dilated_cardiomyopathy$
axm10 : $\neg RAE = LVH_cause$
axm11 : $\neg RAE = NDS6$
axm12 : $\neg RVH = RV_strain$
axm13 : $\neg RVH = pulmonary_embolism$
axm14 : $\neg RVH = LAE$
axm15 : $\neg RVH = mitral_stenosis$
axm16 : $\neg RVH = mitral_regurgitation$
axm17 : $\neg RVH = LV_failure$
axm18 : $\neg RVH = dilated_cardiomyopathy$
axm19 : $\neg RVH = LVH_cause$
axm20 : $\neg RVH = NDS6$
axm21 : $\neg RV_strain = pulmonary_embolism$
axm22 : $\neg RV_strain = LAE$
axm23 : $\neg RV_strain = mitral_stenosis$

axm24 : $\neg RV_strain = mitral_regurgitation$
 axm25 : $\neg RV_strain = LV_failure$
 axm26 : $\neg RV_strain = dilated_cardiomyopathy$
 axm27 : $\neg RV_strain = LVH_cause$
 axm28 : $\neg RV_strain = NDS6$
 axm29 : $\neg pulmonary_embolism = LAE$
 axm30 : $\neg pulmonary_embolism = mitral_stenosis$
 axm31 : $\neg pulmonary_embolism = mitral_regurgitation$
 axm32 : $\neg pulmonary_embolism = LV_failure$
 axm33 : $\neg pulmonary_embolism = dilated_cardiomyopathy$
 axm34 : $\neg pulmonary_embolism = LVH_cause$
 axm35 : $\neg pulmonary_embolism = NDS6$
 axm36 : $\neg LAE = mitral_stenosis$
 axm37 : $\neg LAE = mitral_regurgitation$
 axm38 : $\neg LAE = LV_failure$
 axm39 : $\neg LAE = dilated_cardiomyopathy$
 axm40 : $\neg LAE = LVH_cause$
 axm41 : $\neg LAE = NDS6$
 axm42 : $\neg mitral_stenosis = mitral_regurgitation$
 axm43 : $\neg mitral_stenosis = LV_failure$
 axm44 : $\neg mitral_stenosis = dilated_cardiomyopathy$
 axm45 : $\neg mitral_stenosis = LVH_cause$
 axm46 : $\neg mitral_stenosis = NDS6$
 axm47 : $\neg mitral_regurgitation = LV_failure$
 axm48 : $\neg mitral_regurgitation = dilated_cardiomyopathy$
 axm49 : $\neg mitral_regurgitation = LVH_cause$
 axm50 : $\neg mitral_regurgitation = NDS6$
 axm51 : $\neg LV_failure = dilated_cardiomyopathy$
 axm52 : $\neg LV_failure = LVH_cause$
 axm53 : $\neg LV_failure = NDS6$
 axm54 : $\neg dilated_cardiomyopathy = LVH_cause$
 axm55 : $\neg dilated_cardiomyopathy = NDS6$
 axm56 : $\neg LVH_cause = NDS6$

END

An Event-B Specification of Step6_P_Wave
Generated Date: 25 Nov 2010 @ 03:39:25 PM

MACHINE Step6_P_Wave

REFINES Step5_Q_Waves_Ref1

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
Small_R_QS A small R or QS wave in V1 and V2
Slurred_S_duration Slurred S duration
Delta_Wave Delta Wave
Disease_step3
ST_elevation ST segment elevation (Coved or Saddle-back)
PP_Interval
RR_Interval
Epsilon_Wave Epsilon Wave or (a terminal notch in the QRS)
ST_seg_ele ST segment for elevation 1mm=0.1mV
Disease_step4
Q_Width Q wave width
Q_Depth Q wave depth
Q_Normal_Status Q wave normal or abnormal
Age_of_Inf Age of Infarct
Disease_step5
Mice_State
R_Depth R wave depth or height
R_Normal_Status R wave normal or abnormal
Q_Wave_State Q wave states for all LEADS
P_Wave_Peak function to estimate the peak of LEADS signal
Disease_step6
Diphasic
P_Wave_Broad
ST_depression

INVARIANTS

inv1 : $P_Wave_Peak \in LEADS \rightarrow \mathbb{N}$
inv2 : $Disease_step6 \in Disease_Codes_Step6$
inv3 : $Diphasic \in LEADS \rightarrow BOOL$
inv4 : $P_Wave_Broad \in LEADS \rightarrow \mathbb{N}$
inv5 : $Sinus = Yes \wedge Disease_step6 \in \{RAE, RVH, RV_strain, pulmonary_embolism, LAE, mitral_stenosis, mitral_regurgitation, LV_failure, dilated_cardiomyopathy, LVH_cause\} \Rightarrow Heart_State = KO$

EVENTS

Initialisation

extended

begin

act1 : $RR_Int_equidistant : \in LEADS \rightarrow BOOL$
act2 : $PP_Int_equidistant : \in LEADS \rightarrow BOOL$
act3 : $P_Positive : \in LEADS \rightarrow BOOL$
act4 : $Sinus := No$
act5 : $PP_Interval : \in LEADS \rightarrow \mathbb{N}$
act6 : $RR_Interval : \in LEADS \rightarrow \mathbb{N}$
act7 : $Heart_Rate : \in 1 .. 300$
act8 : $Heart_State := KO$
act9 : $PR_Int := 120$
act10 : $Disease_step2 := NDS2$
act11 : $QRS_Int := 50$
act12 : $Notched_R : \in LEADS \rightarrow BOOL$
act13 : $Small_R_QS : \in LEADS \rightarrow BOOL$
act14 : $Slurred_S_duration : \in LEADS \rightarrow \mathbb{N}_1$
act15 : $M_Shape_Complex : \in LEADS \rightarrow BOOL$
act16 : $Slurred_S : \in LEADS \rightarrow BOOL$
act17 : $ST_elevation : \in LEADS \rightarrow BOOL$
act18 : $Epsilon_Wave : \in LEADS \rightarrow BOOL$
act19 : $Delta_Wave := 0$
act20 : $Disease_step3 := NDS3$
act21 : $ST_seg_ele : \in LEADS \rightarrow \mathbb{N}$
act22 : $Disease_step4 := NDS4$
act57 : $ST_depression : \in LEADS \rightarrow \mathbb{N}$
act23 : $Q_Width : \in LEADS \rightarrow \mathbb{N}$
act24 : $Q_Depth : \in LEADS \rightarrow \mathbb{N}$
act25 : $Q_Normal_Status := FALSE$
act26 : $Mice_State := NMS$
act27 : $R_Depth : \in LEADS \rightarrow \mathbb{N}$
act28 : $R_Normal_Status := FALSE$
act29 : $Q_Wave_State : \in LEADS \rightarrow BOOL$
act30 : $Age_of_Inf : \in Age_of_Infarct$
act31 : $Disease_step5 := NDS5$
act32 : $Diphasic : \in LEADS \rightarrow BOOL$
act33 : $P_Wave_Broad : \in LEADS \rightarrow \mathbb{N}$
act34 : $P_Wave_Peak : \in LEADS \rightarrow \mathbb{N}$
act35 : $Disease_step6 := NDS6$

```

end

Event Rhythm_test.TRUE  $\hat{=}$ 
  Sinus Rhythm with Normal Rate

extends Rhythm_test.TRUE

any
  rate

where
  grd1 : ( $\exists l. l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
    RR_Int_equidistant(l) = TRUE  $\wedge$ 
    RR_Interval(l) = PP_Interval(l))
     $\wedge$ 
    P_Positive(II) = TRUE
  grd4 : rate  $\in$  60..100
    60..100 is the range of normal heart rate
  grd5 : PR_Int  $\leq$  200
    Heart is Normal if PR  $\leq$  200 QRS_Int  $<$  120
    HeartisNormalifQRS  $<$  120
  grd6 : Disease_step2 = NDS2
  grd8 : Disease_step3 = NDS3
  grd9 : Disease_step4 = NDS4
  grd10 : Disease_step5 = NDS5
  grd11 : Disease_step6 = NDS6

then
  act1 : Sinus := Yes
  act2 : Heart_Rate := rate
  act3 : Heart_State := OK

end

Event Rhythm_test.FALSE  $\hat{=}$ 
  Abnormal Rhythm with Rate

extends Rhythm_test.FALSE

any
  rate

where
  grd1 : ( $\forall l. l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \vee$ 
    RR_Int_equidistant(l) = FALSE  $\vee$ 
    RR_Interval(l)  $\neq$  PP_Interval(l))
     $\vee$ 
    P_Positive(II) = FALSE
  grd2 : rate  $\in$  1..300

then
  act1 : Sinus := No
  act2 : Heart_Rate := rate
  act3 : Heart_State := KO

end

Event Rhythm_test.TRUE_Rate  $\hat{=}$ 
  Sinus Rhythm with abnormal Rate

```

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists l \cdot l \in \{II, V1, V2\} \wedge PP_Int_equidistant(l) = TRUE \wedge$
RR_Int_equidistant(l) = TRUE \wedge
RR_Interval(l) = PP_Interval(l))
 \wedge
P_Positive(II) = TRUE

grd5 : rate $\in 1..300 \setminus 60..100$

60..100 is the range of normal heart rate, so rest of no. is abnormal

grd6 : Disease_step3 = WPW_Syndrome \vee Disease_step3 = Brugada_Syndrome \vee
Disease_step3 = RV_Dysplasia \vee Disease_step3 = IVCD

then

act1 : Sinus := Yes

act2 : Heart_Rate := rate

act3 : Heart_State := KO

end

Event *PR_Test* $\hat{=}$

PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : pr $\in 120..220$
time interval in (ms.)

grd2 : pr > 200

grd3 : Sinus = Yes

grd4 : Heart_State = KO

then

act1 : PR_Int := pr

act2 : Disease_step2 := First_degree_AV_Block

end

Event *QRS_Test_LBBB* $\hat{=}$

QRS Complex Interval Test

extends *QRS_Test_LBBB*

any

qrs

where

grd1 : qrs $\in 50..150$

grd2 : qrs ≥ 120

grd3 : Sinus = Yes

grd4 : Heart_State = KO

grd5 : Notched_R(I) = TRUE \wedge
Notched_R(V5) = TRUE \wedge
Notched_R(V6) = TRUE

Right Bundle Branch Block (RBBB)

```

    grd6 : Small_R_QS(V1) = TRUE ∧
           Small_R_QS(V2) = TRUE
    grd7 : Q_Wave_State(V1) = TRUE ∧
           Q_Wave_State(V2) = TRUE ∧
           Q_Wave_State(V3) = TRUE ∧
           Q_Wave_State(V4) = TRUE
           from step 5
    grd8 : R_Normal_Status = FALSE
           from step 5
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := LBBB
  end
Event QRS_Test_RBBB ≐
  Right Bundle Branch Block (RBBB)
extends QRS_Test_RBBB

  any
    qrs
  where
    grd1 : qrs ∈ 50 .. 150
    grd2 : qrs ≥ 120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : M_Shape_Complex(V1) = TRUE ∧
           M_Shape_Complex(V2) = TRUE
    grd7 : Slurred_S(I) = TRUE ∧
           Slurred_S(V5) = TRUE ∧
           Slurred_S(V6) = TRUE
    grd8 : Slurred_S_duration(I) > 40 ∧
           Slurred_S_duration(V5) > 40 ∧
           Slurred_S_duration(V6) > 40
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := RBBB
  end
Event QRS_Test_Atypical_RLBBB_WPW_Syndrome ≐
  QRS Test for Atypical LBBB RBBB
extends QRS_Test_Atypical_RLBBB_WPW_Syndrome

  any
    sympt
    d_wave
    exmi
  where
    grd1 : QRS_Int ≥ 110
    grd2 : sympt = A_RBBB ∨ sympt = A_LBBB
    grd3 : d_wave ∈ ℕ
    grd4 : (d_wave + PR_Int) ≤ 120
           Delta Wave + PR ≤ 120 Heart_State = KO

```

```

    grd6 : Disease_step4 = Acute_inferior_MI
    grd7 : exmi ∈ Mice_State5 ∧ exmi = Exclude_Mimics_MI
  then
    act2 : Delta_Wave := d_wave
    act3 : Disease_step3 := WPW_Syndrome
  end
Event QRS_Test_Atypical_RBBB_Brugada_Syndrome ≐
  Atypical_RBBB_but_WPW_Excluded_and_no_slurred_S_wave_in_V5_and_V6
extends QRS_Test_Atypical_RBBB_Brugada_Syndrome
  any
    sympt
    dis
  where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int ≥ 110
    grd4 : Slurred_S(V5) = FALSE ∧
           Slurred_S(V6) = FALSE
    grd5 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, NDS3}
    grd6 : ST_elevation(V1) = TRUE ∧
           ST_elevation(V2) = TRUE
    grd7 : Sinus = Yes
  then
    act1 : Disease_step3 := Brugada_Syndrome
  end
Event QRS_Test_Atypical_RBBB_RV_Dysplasia ≐
  Right_Ventricular_Dysplasia
extends QRS_Test_Atypical_RBBB_RV_Dysplasia
  any
    sympt
    dis
  where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int ≥ 110
    grd4 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, NDS3}
    grd5 : Epsilon_Wave(V1) = TRUE ∧
           Epsilon_Wave(V3) = TRUE
  then
    act1 : Disease_step3 := RV_Dysplasia
  end
Event QRS_Test_Atypical_RBBB_IVCD ≐
  IVCD_diagnosis
extends QRS_Test_Atypical_RBBB_IVCD
  any

```

```

    dis
  where
    grd1 : QRS_Int ≥ 110
    grd2 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, NDS3}
    grd3 : Heart_State = KO
  then
    act1 : Disease_step3 := IVCD
  end

Event ST_seg_elevation_YES ≐
  ST segment elevation...

refines ST_seg_elevation_YES

  when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :
      ∨
      ((∃ l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
      (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
      ∧
      (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
      ∧ l1 ≠ k1
      ∧
      (
      (l1 = V1 ∧ k1 = V2) ∨
      (l1 = V2 ∧ k1 = V3) ∨
      (l1 = V3 ∧ k1 = V4) ∨
      (l1 = V4 ∧ k1 = V5) ∨
      (l1 = V5 ∧ k1 = V6)
      )
      ))
    grd4 : Disease_step4 ∈ {Acute_inferior_MI, Acute_anterior_MI}
  then
    act1 : Disease_step4 := STEMI
  end

Event ST_seg_elevation_NOTCKMB_Yes ≐
  Troponin or CK-MB positive YES

extends ST_seg_elevation_NOTCKMB_Yes

  when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :
      ∨
      (∀ l1 · l1 ∈ {II, III, aVF} ⇒
      (ST_elevation(l1) = FALSE ∧ ST_seg_ele(l1) < 1000))
    grd4 : ∃ l, k · l ∈ LEADS ∧ k ∈ LEADS ∧
      (ST_depression(l) ≥ 1000 ∧ ST_depression(k) ≥ 1000)
      ∧ l ≠ k
    grd5 : Disease_step4 ∈ {Troponin, CK_MB}
  then
    act1 : Disease_step4 := Non_STEMI

```



```

end

Event ST_seg_elevation_NO_TCKMB_No  $\hat{=}$ 
Troponin or CK-MB positive No

extends ST_seg_elevation_NO_TCKMB_No

when
  grd1 : Heart_State = KO
  grd2 : Sinus = Yes
  grd3 :  $\vee$ 
  ( $\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$ 
  ( $ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000$ ))
grd4 :  $\exists l, k \cdot l \in LEADS \wedge k \in LEADS \wedge$ 
  ( $ST\_depression(l) \geq 1000 \wedge ST\_depression(k) \geq 1000$ 
   $\wedge l \neq k$ )
grd5 : Disease_step4  $\notin$  {Troponin, CK_MB}
then
  act1 : Disease_step4 := Ischemia
end

Event Q_Assessment_Normal  $\hat{=}$ 
Q wave assessment normal

extends Q_Assessment_Normal

when
  grd1 : Q_Width(II) < 40  $\wedge$  Q_Depth(II)  $\leq$  3000  $\wedge$ 
  Q_Width(aVF) < 40  $\wedge$  Q_Depth(aVF)  $\leq$  3000  $\wedge$ 
  Q_Width(aVL) < 40
  1000 micrometer = 1 millimeter
  grd2 : Q_Width(III)  $\leq$  40  $\wedge$  Q_Depth(III)  $\leq$  7000  $\wedge$  Q_Depth(aVL)  $\leq$  7000
  grd3 : Q_Depth(I) < 40  $\wedge$  Q_Depth(I)  $\leq$  1500
then
  act1 : Q_Normal_Status := TRUE
end

Event Q_Assessment_Abnormal_AMI  $\hat{=}$ 
Q wave assessment abnormal for anterolateral MI (AMI)

extends Q_Assessment_Abnormal_AMI

when
  grd1 : Heart_State = KO
  grd2 : Sinus = Yes
  grd3 :  $\vee$ 
  ( $(\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
  ( $ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE$ )
   $\wedge$ 
  ( $ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000$ )
   $\wedge l1 \neq k1$ )
   $\wedge$ 
  (
  ( $l1 = V1 \wedge k1 = V2$ )  $\vee$ 
  ( $l1 = V2 \wedge k1 = V3$ )  $\vee$ 
  ( $l1 = V3 \wedge k1 = V4$ )  $\vee$ 

```

```

        (l1 = V4 ∧ k1 = V5) ∨
        (l1 = V5 ∧ k1 = V6)
    )
))
grd4 : Q_Width(V5) ≥ 40 ∧ Q_Depth(V5) > 3000 ∧
      Q_Width(V6) ≥ 40 ∧ Q_Depth(V6) > 3000
grd5 : Q_Width(aVL) ≥ 40 ∧ Q_Depth(aVL) > 7000
grd6 : Q_Depth(I) ≥ 40 ∧ Q_Depth(I) > 1500
grd7 : Q_Normal.Status = FALSE
    then
        act1 : Disease_step4 := Acute_anterior_MI
    end
Event Q_Assessment_Abnormal_IMI ≐
    Q wave assessment abnormal for inferior MI (IMI)
extends Q_Assessment_Abnormal_IMI
    when
        grd1 : Heart_State = KO
        grd2 : Sinus = Yes
        grd3 :
            ∨
            ((∃ l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
              (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
              ∧
              (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
              ∧ l1 ≠ k1
              ∧
              (
                (l1 = V1 ∧ k1 = V2) ∨
                (l1 = V2 ∧ k1 = V3) ∨
                (l1 = V3 ∧ k1 = V4) ∨
                (l1 = V4 ∧ k1 = V5) ∨
                (l1 = V5 ∧ k1 = V6)
              )
            )
        ))
grd4 : Q_Width(II) ≥ 40 ∧ Q_Depth(II) > 3000 ∧
      Q_Width(III) > 40 ∧ Q_Depth(III) > 7000 ∧
      Q_Width(aVF) ≥ 40 ∧ Q_Depth(aVF) > 3000
grd5 : Q_Normal.Status = FALSE
    then
        act1 : Disease_step4 := Acute_inferior_MI
    end
Event Determine_Age_of_Infarct ≐
extends Determine_Age_of_Infarct
    when
        grd1 : Disease_step4 = Acute_inferior_MI
            ∨
            Disease_step5 ∈ {anterior_MI, LVH, emphysema}
            ∨
            Mice_State = Exclude_Mimics_MI
            ∨
            Disease_step2 = LBBB

```

```

    then
        act1 : Age_of_Inf :∈ {recent,old,indeterminate}
    end
Event Exclude_Mimics ≐
extends Exclude_Mimics
    any
        exmi
    where
        grd1 : Disease_step4 = Acute_inferior_MI
        grd2 : exmi ∈ Mice_State5 ∧ exmi = Exclude_Mimics_MI
    then
        act1 : Disease_step5 := Hypertrophic_cardiomyopathy
        act2 : Mice_State := borderline_Qs
    end
Event R_Assessment_Normal ≐
    Q wave assessment normal
extends R_Assessment_Normal
    any
        age
    where
        grd1 : R.Depth(V1) ≥ 0 ∧ R.Depth(V1) ≤ 6000 ∧ age > 30
            1000 micrometer = 1 millimeter
        grd2 : R.Depth(V2) > 200 ∧ R.Depth(V2) ≤ 12000
        grd3 : R.Depth(V2) ≥ 1000 ∧ R.Depth(V2) ≤ 24000
    then
        act1 : R.Normal_Status := TRUE
    end
Event R_Assessment_Abnormal ≐
extends R_Assessment_Abnormal
    when
        grd1 : R.Normal_Status = FALSE
    then
        act1 : Mice_State :∈ {late_transition,normal_variant}
    end
Event R_Q_Assessment_R_Abnormal_V1234 ≐
    R wave abnormal , pathologic Q waves consider in V1-V4
extends R_Q_Assessment_R_Abnormal_V1234
    when
        grd1 : R.Normal_Status = FALSE
        grd2 : Q.Wave_State(V1) = TRUE ∧
            Q.Wave_State(V2) = TRUE ∧
            Q.Wave_State(V3) = TRUE ∧
            Q.Wave_State(V4) = TRUE

```

```

    grd3 : Heart_State = KO
  then
    act1 : Disease_step5 :∈ {anterior_MI, LVH, emphysema}
    act2 : Mice_State := Exclude_Mimics_MI
  end
Event R_Q_Assessment_R_Abnormal_V56 ≐
  R wave abnormal , pathologic Q waves consider in V5-V6
extends R_Q_Assessment_R_Abnormal_V56
  when
    grd1 : Q_Wave_State(V5) = TRUE ∧
           Q_Wave_State(V6) = TRUE
    grd3 : Heart_State = KO
  then
    act1 : Disease_step5 :∈ {lateral_MI, Hypertrophic_cardiomyopathy}
  end
Event P_Wave_assessment_Peaked_Yes ≐
  when
    grd1 : P_Wave_Peak(II) ≥ 3000
    grd2 : P_Wave_Peak(V1) ≥ 3000
    grd3 : Heart_State = KO
  then
    act1 : Disease_step6 :∈ {RAE, RVH, RV_strain, pulmonary_embolism}
  end
Event P_Wave_assessment_Peaked_Broad_No ≐
  when
    grd1 : (P_Wave_Peak(II) < 3000 ∧
           P_Wave_Peak(V1) < 3000)
           ∨
           (P_Wave_Broad(II) < 110 ∧ P_Wave_Broad(V1) < 110) ∨
           Diphasic(II) = FALSE ∨
           Diphasic(V1) = FALSE
  then
    act1 : Disease_step6 := NDS6
  end
Event P_Wave_assessment_Broad_Yes ≐
  when
    grd1 : (P_Wave_Broad(II) ≥ 110 ∧ P_Wave_Broad(V1) ≥ 110) ∨
           Diphasic(II) = TRUE ∨
           Diphasic(V1) = TRUE
    grd2 : Heart_State = KO
  then
    act1 : Disease_step6 :∈ {LAE, mitral_stenosis, mitral_regurgitation, LV_failure,
                             dilated_cardiomyopathy, LVH_cause}
  end
END

```

An Event-B Specification of Step6_P_Wave_Ref1
Generated Date: 25 Nov 2010 @ 03:39:29 PM

MACHINE Step6_P_Wave_Ref1

REFINES Step6_P_Wave

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
Small_R_QS A small R or QS wave in V1 and V2
Slurred_S_duration Slurred S duration
Delta_Wave Delta Wave
Disease_step3
ST_elevation ST segment elevation (Coved or Saddle-back)
Epsilon_Wave Epsilon Wave or (a terminal notch in the QRS)
PP_Interval
RR_Interval
ST_seg_ele ST segment for elevation 1mm=0.1mV
Disease_step4
Q_Width Q wave width
Q_Depth Q wave depth
Q_Normal_Status Q wave normal or abnormal
Age_of_Inf Age of Infarct
Disease_step5
Mice_State
R_Depth R wave depth or height
R_Normal_Status R wave normal or abnormal
Q_Wave_State Q wave states for all LEADS
P_Wave_Peak function to estimate the peak of LEADS signal
Disease_step6
Diphasic
P_Wave_Broad
ST_depression

INVARIANTS

inv1 : $Sinus = Yes \wedge Disease_step6 = LAE \Rightarrow Heart_State = KO$

inv2 : $Sinus = Yes \wedge Disease_step6 = RAE \Rightarrow Heart_State = KO$

EVENTS

Initialisation

extended

begin

act1 : $RR_Int_equidistant : \in LEADS \rightarrow BOOL$
act2 : $PP_Int_equidistant : \in LEADS \rightarrow BOOL$
act3 : $P_Positive : \in LEADS \rightarrow BOOL$
act4 : $Sinus := No$
act5 : $PP_Interval : \in LEADS \rightarrow \mathbb{N}$
act6 : $RR_Interval : \in LEADS \rightarrow \mathbb{N}$
act7 : $Heart_Rate : \in 1..300$
act8 : $Heart_State := KO$
act9 : $PR_Int := 120$
act10 : $Disease_step2 := NDS2$
act11 : $QRS_Int := 50$
act12 : $Notched_R : \in LEADS \rightarrow BOOL$
act13 : $Small_R_QS : \in LEADS \rightarrow BOOL$
act14 : $Slurred_S_duration : \in LEADS \rightarrow \mathbb{N}_1$
act15 : $M_Shape_Complex : \in LEADS \rightarrow BOOL$
act16 : $Slurred_S : \in LEADS \rightarrow BOOL$
act17 : $ST_elevation : \in LEADS \rightarrow BOOL$
act18 : $Epsilon_Wave : \in LEADS \rightarrow BOOL$
act19 : $Delta_Wave := 0$
act20 : $Disease_step3 := NDS3$
act21 : $ST_seg_ele : \in LEADS \rightarrow \mathbb{N}$
act22 : $Disease_step4 := NDS4$
act57 : $ST_depression : \in LEADS \rightarrow \mathbb{N}$
act23 : $Q_Width : \in LEADS \rightarrow \mathbb{N}$
act24 : $Q_Depth : \in LEADS \rightarrow \mathbb{N}$
act25 : $Q_Normal_Status := FALSE$
act26 : $Mice_State := NMS$
act27 : $R_Depth : \in LEADS \rightarrow \mathbb{N}$
act28 : $R_Normal_Status := FALSE$
act29 : $Q_Wave_State : \in LEADS \rightarrow BOOL$
act30 : $Age_of_Inf : \in Age_of_Infarct$
act31 : $Disease_step5 := NDS5$
act32 : $Diphasic : \in LEADS \rightarrow BOOL$
act33 : $P_Wave_Broad : \in LEADS \rightarrow \mathbb{N}$
act34 : $P_Wave_Peak : \in LEADS \rightarrow \mathbb{N}$
act35 : $Disease_step6 := NDS6$

end

Event *Rhythm_test_TRUE* $\hat{=}$
Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

```

any
  rate
where
  grd1 : ( $\exists l. l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
           $RR\_Int\_equidistant(l) = TRUE \wedge$ 
           $RR\_Interval(l) = PP\_Interval(l)$ 
           $\wedge$ 
           $P\_Positive(II) = TRUE$ )
  grd4 : rate  $\in 60..100$ 
          60..100 is the range of normal heart rate
  grd5 : PR.Int  $\leq 200$ 
          Heart is Normal if PR  $\leq 200$  QRS.Int  $< 120$ 
          HeartisNormalifQRS < 120
  grd6
  grd7 : Disease_step2 = NDS2
  grd8 : Disease_step3 = NDS3
  grd9 : Disease_step4 = NDS4
  grd10 : Disease_step5 = NDS5
  grd11 : Disease_step6 = NDS6
then
  act1 : Sinus := Yes
  act2 : Heart_Rate := rate
  act3 : Heart_State := OK
end

Event Rhythm_test_FALSE  $\hat{=}$ 
  Abnormal Rhythm with Rate

extends Rhythm_test_FALSE

any
  rate
where
  grd1 : ( $\forall l. l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \vee$ 
           $RR\_Int\_equidistant(l) = FALSE \vee$ 
           $RR\_Interval(l) \neq PP\_Interval(l)$ 
           $\vee$ 
           $P\_Positive(II) = FALSE$ )
  grd2 : rate  $\in 1..300$ 
then
  act1 : Sinus := No
  act2 : Heart_Rate := rate
  act3 : Heart_State := KO
end

Event Rhythm_test.TRUE_Rate  $\hat{=}$ 
  Sinus Rhythm with abnormal Rate

extends Rhythm_test.TRUE_Rate

any
  rate
where

```

```

    grd1 : ( $\exists l. l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
            RR_Int_equidistant(l) = TRUE  $\wedge$ 
            RR_Interval(l) = PP_Interval(l))
             $\wedge$ 
            P_Positive(II) = TRUE
    grd5 : rate  $\in 1..300 \setminus 60..100$ 
            60..100 is the range of normal heart rate, so rest of no. is abnormal
    grd6 : Disease_step3 = WPW_Syndrome  $\vee$  Disease_step3 = Brugada_Syndrome  $\vee$ 
            Disease_step3 = RV_Dysplasia  $\vee$  Disease_step3 = IVCD

    then
        act1 : Sinus := Yes
        act2 : Heart_Rate := rate
        act3 : Heart_State := KO
    end

Event PR_Test  $\hat{=}$ 
    PR_Interval_Test

extends PR_Test

    any
        pr
    where
        grd1 : pr  $\in 120..220$ 
                time interval in (ms.)
        grd2 : pr > 200
        grd3 : Sinus = Yes
        grd4 : Heart_State = KO
    then
        act1 : PR_Int := pr
        act2 : Disease_step2 := First_degree_AV_Block
    end

Event QRS_Test_LBBB  $\hat{=}$ 
    QRS_Complex_Interval_Test

extends QRS_Test_LBBB

    any
        qrs
    where
        grd1 : qrs  $\in 50..150$ 
        grd2 : qrs  $\geq 120$ 
        grd3 : Sinus = Yes
        grd4 : Heart_State = KO
        grd5 : Notched_R(I) = TRUE  $\wedge$ 
                Notched_R(V5) = TRUE  $\wedge$ 
                Notched_R(V6) = TRUE
                Right_Bundle_Branch_Block (RBBB)
        grd6 : Small_R_QS(V1) = TRUE  $\wedge$ 
                Small_R_QS(V2) = TRUE

```



```

    grd7 : Q_Wave_State(V1) = TRUE ∧
           Q_Wave_State(V2) = TRUE ∧
           Q_Wave_State(V3) = TRUE ∧
           Q_Wave_State(V4) = TRUE
           from step 5
    grd8 : R_Normal_Status = FALSE
           from step 5
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := LBBB
  end

Event QRS_Test_RBBB  $\hat{=}$ 
  Right Bundle Branch Block (RBBB)

extends QRS_Test_RBBB

  any
    qrs
  where
    grd1 : qrs  $\in$  50 .. 150
    grd2 : qrs  $\geq$  120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : M_Shape_Complex(V1) = TRUE ∧
           M_Shape_Complex(V2) = TRUE
    grd7 : Slurred_S(I) = TRUE ∧
           Slurred_S(V5) = TRUE ∧
           Slurred_S(V6) = TRUE
    grd8 : Slurred_S_duration(I) > 40 ∧
           Slurred_S_duration(V5) > 40 ∧
           Slurred_S_duration(V6) > 40
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := RBBB
  end

Event QRS_Test_Atypical_RLBBB_WPW_Syndrome  $\hat{=}$ 
  QRS Test for Atypical LBBB RBBB

extends QRS_Test_Atypical_RLBBB_WPW_Syndrome

  any
    sympt
    d_wave
    exmi
  where
    grd1 : QRS_Int  $\geq$  110
    grd2 : sympt = A_RBBB  $\vee$  sympt = A_LBBB
    grd3 : d_wave  $\in$   $\mathbb{N}$ 
    grd4 : (d_wave + PR_Int)  $\leq$  120
           Delta Wave + PR  $\leq$  120 Heart_State = KO
    grd5 : Disease_step4 = Acute_inferior_MI

```

```

    grd7 : exmi ∈ Mice_State5 ∧ exmi = Exclude_Mimics_MI
  then
    act2 : Delta_Wave := d_wave
    act3 : Disease_step3 := WPW_Syndrome
  end
Event QRS_Test_Atypical_RBBB_Brugada_Syndrome ≐
  Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6
extends QRS_Test_Atypical_RBBB_Brugada_Syndrome
  any
    sympt
    dis
  where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int ≥ 110
    grd4 : Slurred_S(V5) = FALSE ∧
           Slurred_S(V6) = FALSE
    grd5 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, NDS3}
    grd6 : ST_elevation(V1) = TRUE ∧
           ST_elevation(V2) = TRUE
    grd7 : Sinus = Yes
  then
    act1 : Disease_step3 := Brugada_Syndrome
  end
Event QRS_Test_Atypical_RBBB_RV_Dysplasia ≐
  Right Ventricular Dysplasia
extends QRS_Test_Atypical_RBBB_RV_Dysplasia
  any
    sympt
    dis
  where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int ≥ 110
    grd4 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, NDS3}
    grd5 : Epsilon_Wave(V1) = TRUE ∧
           Epsilon_Wave(V3) = TRUE
  then
    act1 : Disease_step3 := RV_Dysplasia
  end
Event QRS_Test_Atypical_RBBB_IVCD ≐
  IVCD diagnosis
extends QRS_Test_Atypical_RBBB_IVCD
  any

```

```

    dis
  where
    grd1 : QRS_Int ≥ 110
    grd2 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, NDS3}
    grd3 : Heart_State = KO
  then
    act1 : Disease_step3 := IVCD
  end

Event ST_seg_elevation_YES ≐
  ST segment elevation...

extends ST_seg_elevation_YES

  when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :
      ∨
      ((∃ l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
      (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
      ∧
      (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
      ∧ l1 ≠ k1
      ∧
      (
      (l1 = V1 ∧ k1 = V2) ∨
      (l1 = V2 ∧ k1 = V3) ∨
      (l1 = V3 ∧ k1 = V4) ∨
      (l1 = V4 ∧ k1 = V5) ∨
      (l1 = V5 ∧ k1 = V6)
      )
      ))
    grd4 : Disease_step4 ∈ {Acute_inferior_MI, Acute_anterior_MI}
  then
    act1 : Disease_step4 := STEMI
  end

Event ST_seg_elevation_NOTCKMB_Yes ≐
  Troponin or CK-MB positive YES

extends ST_seg_elevation_NOTCKMB_Yes

  when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :
      ∨
      (∀ l1 · l1 ∈ {II, III, aVF} ⇒
      (ST_elevation(l1) = FALSE ∧ ST_seg_ele(l1) < 1000))
    grd4 : ∃ l, k · l ∈ LEADS ∧ k ∈ LEADS ∧
      (ST_depression(l) ≥ 1000 ∧ ST_depression(k) ≥ 1000)
      ∧ l ≠ k
    grd5 : Disease_step4 ∈ {Troponin, CK_MB}
  then
    act1 : Disease_step4 := Non_STEMI

```

```

end

Event ST_seg_elevation_NO_TCKMB_No  $\hat{=}$ 
Troponin or CK-MB positive No

extends ST_seg_elevation_NO_TCKMB_No

when
  grd1 : Heart_State = KO
  grd2 : Sinus = Yes
  grd3 :  $\vee$ 
  ( $\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$ 
  ( $ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000$ ))
grd4 :  $\exists l, k \cdot l \in LEADS \wedge k \in LEADS \wedge$ 
  ( $ST\_depression(l) \geq 1000 \wedge ST\_depression(k) \geq 1000$ 
   $\wedge l \neq k$ )
grd5 : Disease_step4  $\notin$  {Troponin, CK_MB}
then
  act1 : Disease_step4 := Ischemia
end

Event Q_Assessment_Normal  $\hat{=}$ 
Q wave assessment normal

extends Q_Assessment_Normal

when
  grd1 : Q_Width(II) < 40  $\wedge$  Q_Depth(II)  $\leq$  3000  $\wedge$ 
  Q_Width(aVF) < 40  $\wedge$  Q_Depth(aVF)  $\leq$  3000  $\wedge$ 
  Q_Width(aVL) < 40
  1000 micrometer = 1 millimeter
  grd2 : Q_Width(III)  $\leq$  40  $\wedge$  Q_Depth(III)  $\leq$  7000  $\wedge$  Q_Depth(aVL)  $\leq$  7000
  grd3 : Q_Depth(I) < 40  $\wedge$  Q_Depth(I)  $\leq$  1500
then
  act1 : Q_Normal_Status := TRUE
end

Event Q_Assessment_Abnormal_AMI  $\hat{=}$ 
Q wave assessment abnormal for anterolateral MI (AMI)

extends Q_Assessment_Abnormal_AMI

when
  grd1 : Heart_State = KO
  grd2 : Sinus = Yes
  grd3 :  $\vee$ 
  ( $(\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
  ( $ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE$ )
   $\wedge$ 
  ( $ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000$ )
   $\wedge l1 \neq k1$ 
   $\wedge$ 
  (
  ( $l1 = V1 \wedge k1 = V2$ )  $\vee$ 
  ( $l1 = V2 \wedge k1 = V3$ )  $\vee$ 
  ( $l1 = V3 \wedge k1 = V4$ )  $\vee$ 

```

```

        (l1 = V4 ∧ k1 = V5) ∨
        (l1 = V5 ∧ k1 = V6)
    )
))
grd4 : Q_Width(V5) ≥ 40 ∧ Q_Depth(V5) > 3000 ∧
      Q_Width(V6) ≥ 40 ∧ Q_Depth(V6) > 3000
grd5 : Q_Width(aVL) ≥ 40 ∧ Q_Depth(aVL) > 7000
grd6 : Q_Depth(I) ≥ 40 ∧ Q_Depth(I) > 1500
grd7 : Q_Normal.Status = FALSE
    then
        act1 : Disease_step4 := Acute_anterior_MI
    end
Event Q_Assessment_Abnormal_IMI ≐
    Q wave assessment abnormal for inferior MI (IMI)
extends Q_Assessment_Abnormal_IMI
    when
        grd1 : Heart_State = KO
        grd2 : Sinus = Yes
        grd3 :
            ∨
            ((∃ l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
            (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
            ∧
            (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
            ∧ l1 ≠ k1
            ∧
            (
            (l1 = V1 ∧ k1 = V2) ∨
            (l1 = V2 ∧ k1 = V3) ∨
            (l1 = V3 ∧ k1 = V4) ∨
            (l1 = V4 ∧ k1 = V5) ∨
            (l1 = V5 ∧ k1 = V6)
            )
            ))
grd4 : Q_Width(II) ≥ 40 ∧ Q_Depth(II) > 3000 ∧
      Q_Width(III) > 40 ∧ Q_Depth(III) > 7000 ∧
      Q_Width(aVF) ≥ 40 ∧ Q_Depth(aVF) > 3000
grd5 : Q_Normal.Status = FALSE
    then
        act1 : Disease_step4 := Acute_inferior_MI
    end
Event Determine_Age_of_Infarct ≐
extends Determine_Age_of_Infarct
    when
        grd1 : Disease_step4 = Acute_inferior_MI
            ∨
            Disease_step5 ∈ {anterior_MI, LVH, emphysema}
            ∨
            Mice_State = Exclude_Mimics_MI
            ∨
            Disease_step2 = LBBB

```

```

    then
        act1 : Age_of_Inf :∈ {recent,old,indeterminate}
    end
Event Exclude_Mimics ≐
extends Exclude_Mimics
    any
        exmi
    where
        grd1 : Disease_step4 = Acute_inferior_MI
        grd2 : exmi ∈ Mice_State5 ∧ exmi = Exclude_Mimics_MI
    then
        act1 : Disease_step5 := Hypertrophic_cardiomyopathy
        act2 : Mice_State := borderline_Qs
    end
Event R_Assessment_Normal ≐
    Q wave assessment normal
extends R_Assessment_Normal
    any
        age
    where
        grd1 : R.Depth(V1) ≥ 0 ∧ R.Depth(V1) ≤ 6000 ∧ age > 30
            1000 micrometer= 1 millimeter
        grd2 : R.Depth(V2) > 200 ∧ R.Depth(V2) ≤ 12000
        grd3 : R.Depth(V2) ≥ 1000 ∧ R.Depth(V2) ≤ 24000
    then
        act1 : R.Normal_Status := TRUE
    end
Event R_Assessment_Abnormal ≐
extends R_Assessment_Abnormal
    when
        grd1 : R.Normal_Status = FALSE
    then
        act1 : Mice_State :∈ {late_transition,normal_variant}
    end
Event R_Q_Assessment_R_Abnormal_V1234 ≐
    R wave abnormal , pathologic Q waves consider in V1-V4
extends R_Q_Assessment_R_Abnormal_V1234
    when
        grd1 : R.Normal_Status = FALSE
        grd2 : Q.Wave_State(V1) = TRUE ∧
            Q.Wave_State(V2) = TRUE ∧
            Q.Wave_State(V3) = TRUE ∧
            Q.Wave_State(V4) = TRUE

```

```

    grd3 : Heart_State = KO
  then
    act1 : Disease_step5 ∈ {anterior_MI, LVH, emphysema}
    act2 : Mice_State := Exclude_Mimics_MI
  end
Event R_Q_Assessment_R_Abnormal_V56 ≐
  R wave abnormal , pathologic Q waves consider in V5-V6
extends R_Q_Assessment_R_Abnormal_V56
  when
    grd1 : Q_Wave_State(V5) = TRUE ∧
           Q_Wave_State(V6) = TRUE
    grd3 : Heart_State = KO
  then
    act1 : Disease_step5 ∈ {lateral_MI, Hypertrophic_cardiomyopathy}
  end
Event P_Wave_assessment_Peaked_Broad_No ≐
extends P_Wave_assessment_Peaked_Broad_No
  when
    grd1 : (P_Wave_Peak(II) < 3000 ∧
           P_Wave_Peak(V1) < 3000)
           ∨
           (P_Wave_Broad(II) < 110 ∧ P_Wave_Broad(V1) < 110) ∨
           Diphasic(II) = FALSE ∨
           Diphasic(V1) = FALSE
  then
    act1 : Disease_step6 := NDS6
  end
Event P_Wave_assessment_Peaked_Yes ≐
refines P_Wave_assessment_Peaked_Yes
  when
    grd1 : P_Wave_Peak(II) ≥ 3000
    grd2 : P_Wave_Peak(V1) ≥ 3000
    grd3 : Heart_State = KO
  then
    act1 : Disease_step6 := RAE
  end
Event P_Wave_assessment_Peaked_Yes_Check_RAE ≐
refines P_Wave_assessment_Peaked_Yes
  when
    grd1 : P_Wave_Peak(II) ≥ 3000
    grd2 : P_Wave_Peak(V1) ≥ 3000
    grd3 : Heart_State = KO
    grd4 : Disease_step6 = RAE

```

```

then
  act1 : Disease_step6 :∈ {RVH, RV_strain, pulmonary_embolism}
end

Event P_Wave_assessment_Broad_Yes ≐
refines P_Wave_assessment_Broad_Yes

  when
    grd1 : (P_Wave_Broad(II) ≥ 110 ∧ P_Wave_Broad(V1) ≥ 110) ∨
      Diphasic(II) = TRUE ∨
      Diphasic(V1) = TRUE
    grd2 : Heart_State = KO
  then
    act1 : Disease_step6 := LAE
  end

Event P_Wave_assessment_Broad_Yes_Check_LAE ≐
refines P_Wave_assessment_Broad_Yes

  when
    grd1 : (P_Wave_Broad(II) ≥ 110 ∧ P_Wave_Broad(V1) ≥ 110) ∨
      Diphasic(II) = TRUE ∨
      Diphasic(V1) = TRUE
    grd2 : Heart_State = KO
    grd3 : Disease_step6 = LAE
  then
    act1 : Disease_step6 :∈ {mitral_stenosis, mitral_regurgitation, LV_failure,
      dilated_cardiomyopathy, LVH_cause}
  end

END

```


An Event-B Specification of Step7_LVH_RVH
Generated Date: 25 Nov 2010 @ 03:39:32 PM

MACHINE Step7_LVH_RVH

REFINES Step6_P_Wave_Ref1

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
Small_R_QS A small R or QS wave in V1 and V2
Slurred_S_duration Slurred S duration
Delta_Wave Delta Wave
Disease_step3
ST_elevation ST segment elevation (Coved or Saddle-back)
Epsilon_Wave Epsilon Wave or (a terminal notch in the QRS)
ST_seg_ele ST segment for elevation 1mm=0.1mV
Disease_step4
Q_Width Q wave width
PP_Interval
RR_Interval
Q_Depth Q wave depth
Q_Normal_Status Q wave normal or abnormal
Age_of_Inf Age of Infarct
Disease_step5
Mice_State
R_Depth R wave depth or height (also use in Step 7)
R_Normal_Status R wave normal or abnormal
Q_Wave_State Q wave states for all LEADS
P_Wave_Peak function to estimate the peak of LEADS signal
Disease_step6
Diphasic
P_Wave_Broad
S_Depth S wave depth or height

R_S_Ratio R wave and S wave Ratio function
ST_depression

INVARIANTS

inv1 : $S_Depth \in LEADS \rightarrow \mathbb{N}$
inv2 : $R_S_Ratio \in LEADS \rightarrow \mathbb{N}$
inv3 : $Sinus = Yes \wedge Disease_step6 = RVH \Rightarrow Heart_State = KO$
inv4 : $Sinus = Yes \wedge Disease_step6 = LVH_cause \Rightarrow Heart_State = KO$

EVENTS

Initialisation

extended

begin

act1 : $RR_Int_equidistant \in LEADS \rightarrow BOOL$
act2 : $PP_Int_equidistant \in LEADS \rightarrow BOOL$
act3 : $P_Positive \in LEADS \rightarrow BOOL$
act4 : $Sinus := No$
act5 : $PP_Interval \in LEADS \rightarrow \mathbb{N}$
act6 : $RR_Interval \in LEADS \rightarrow \mathbb{N}$
act7 : $Heart_Rate \in 1..300$
act8 : $Heart_State := KO$
act9 : $PR_Int := 120$
act10 : $Disease_step2 := NDS2$
act11 : $QRS_Int := 50$
act12 : $Notched_R \in LEADS \rightarrow BOOL$
act13 : $Small_R_QS \in LEADS \rightarrow BOOL$
act14 : $Slurred_S_duration \in LEADS \rightarrow \mathbb{N}_1$
act15 : $M_Shape_Complex \in LEADS \rightarrow BOOL$
act16 : $Slurred_S \in LEADS \rightarrow BOOL$
act17 : $ST_elevation \in LEADS \rightarrow BOOL$
act18 : $Epsilon_Wave \in LEADS \rightarrow BOOL$
act19 : $Delta_Wave := 0$
act20 : $Disease_step3 := NDS3$
act21 : $ST_seg_ele \in LEADS \rightarrow \mathbb{N}$
act22 : $Disease_step4 := NDS4$
act57 : $ST_depression \in LEADS \rightarrow \mathbb{N}$
act23 : $Q_Width \in LEADS \rightarrow \mathbb{N}$
act24 : $Q_Depth \in LEADS \rightarrow \mathbb{N}$
act25 : $Q_Normal_Status := FALSE$
act26 : $Mice_State := NMS$
act27 : $R_Depth \in LEADS \rightarrow \mathbb{N}$
act28 : $R_Normal_Status := FALSE$
act29 : $Q_Wave_State \in LEADS \rightarrow BOOL$
act30 : $Age_of_Inf \in Age_of_Infarct$
act31 : $Disease_step5 := NDS5$
act32 : $Diphasic \in LEADS \rightarrow BOOL$
act33 : $P_Wave_Broad \in LEADS \rightarrow \mathbb{N}$
act34 : $P_Wave_Peak \in LEADS \rightarrow \mathbb{N}$
act35 : $Disease_step6 := NDS6$

```

act36 :  $S\_Depth : \in LEADS \rightarrow \mathbb{N}$ 
act37 :  $R\_S\_Ratio : \in LEADS \rightarrow \mathbb{N}$ 

end

Event Rhythm_test_TRUE  $\hat{=}$ 
  Sinus Rhythm with Normal Rate

extends Rhythm_test_TRUE

any
  rate
where
  grd1 :  $(\exists l. l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
     $RR\_Int\_equidistant(l) = TRUE \wedge$ 
     $RR\_Interval(l) = PP\_Interval(l))$ 
     $\wedge$ 
     $P\_Positive(II) = TRUE$ 
  grd4 :  $rate \in 60..100$ 
    60..100 is the range of normal heart rate
  grd5 :  $PR\_Int \leq 200$ 
    Heart is Normal if  $PR \leq 200$   $QRS\_Int < 120$ 
    HeartisNormalifQRS < 120
  grd6
  grd7 :  $Disease\_step2 = NDS2$ 
  grd8 :  $Disease\_step3 = NDS3$ 
  grd9 :  $Disease\_step4 = NDS4$ 
  grd10 :  $Disease\_step5 = NDS5$ 
  grd11 :  $Disease\_step6 = NDS6$ 

then
  act1 :  $Sinus := Yes$ 
  act2 :  $Heart\_Rate := rate$ 
  act3 :  $Heart\_State := OK$ 

end

Event Rhythm_test_FALSE  $\hat{=}$ 
  Abnormal Rhythm with Rate

extends Rhythm_test_FALSE

any
  rate
where
  grd1 :  $(\forall l. l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \vee$ 
     $RR\_Int\_equidistant(l) = FALSE \vee$ 
     $RR\_Interval(l) \neq PP\_Interval(l))$ 
     $\vee$ 
     $P\_Positive(II) = FALSE$ 
  grd2 :  $rate \in 1..300$ 

then
  act1 :  $Sinus := No$ 
  act2 :  $Heart\_Rate := rate$ 
  act3 :  $Heart\_State := KO$ 

end

```

Event *Rhythm_test_TRUE_Rate* $\hat{=}$
Sinus Rhythm with abnormal Rate

extends *Rhythm_test_TRUE_Rate*

any

rate

where

grd1 : $(\exists l. l \in \{II, V1, V2\} \wedge PP_Int_equidistant(l) = TRUE \wedge$
RR_Int_equidistant(l) = TRUE \wedge
RR_Interval(l) = PP_Interval(l))
 \wedge
P_Positive(II) = TRUE

grd5 : rate $\in 1..300 \setminus 60..100$

60..100 is the range of normal heart rate, so rest of no. is abnormal

grd6 : Disease_step3 = WPW_Syndrome \vee Disease_step3 = Brugada_Syndrome \vee
Disease_step3 = RV_Dysplasia \vee Disease_step3 = IVCD

then

act1 : Sinus := Yes

act2 : Heart_Rate := rate

act3 : Heart_State := KO

end

Event *PR_Test* $\hat{=}$
PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : pr $\in 120..220$
time interval in (ms.)

grd2 : pr > 200

grd3 : Sinus = Yes

grd4 : Heart_State = KO

then

act1 : PR_Int := pr

act2 : Disease_step2 := First_degree_AV_Block

end

Event *QRS_Test_LBBB* $\hat{=}$
QRS Complex Interval Test

extends *QRS_Test_LBBB*

any

qrs

where

grd1 : qrs $\in 50..150$

grd2 : qrs ≥ 120

grd3 : Sinus = Yes

grd4 : Heart_State = KO

```

    grd5 : Notched_R(I) = TRUE ∧
           Notched_R(V5) = TRUE ∧
           Notched_R(V6) = TRUE
           Right Bundle Branch Block (RBBB)
    grd6 : Small_R_QS(V1) = TRUE ∧
           Small_R_QS(V2) = TRUE
    grd7 : Q_Wave_State(V1) = TRUE ∧
           Q_Wave_State(V2) = TRUE ∧
           Q_Wave_State(V3) = TRUE ∧
           Q_Wave_State(V4) = TRUE
           from step 5
    grd8 : R_Normal_Status = FALSE
           from step 5
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := LBBB
  end
Event QRS_Test_RBBB ≐
  Right Bundle Branch Block (RBBB)
extends QRS_Test_RBBB
  any
    qrs
  where
    grd1 : qrs ∈ 50 .. 150
    grd2 : qrs ≥ 120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : M_Shape_Complex(V1) = TRUE ∧
           M_Shape_Complex(V2) = TRUE
    grd7 : Slurred_S(I) = TRUE ∧
           Slurred_S(V5) = TRUE ∧
           Slurred_S(V6) = TRUE
    grd8 : Slurred_S_duration(I) > 40 ∧
           Slurred_S_duration(V5) > 40 ∧
           Slurred_S_duration(V6) > 40
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := RBBB
  end
Event QRS_Test_Atypical_RLBBB_WPW_Syndrome ≐
  QRS Test for Atypical LBBB RBBB
extends QRS_Test_Atypical_RLBBB_WPW_Syndrome
  any
    sympt
    d_wave
    exmi
  where
    grd1 : QRS_Int ≥ 110

```

```

    grd2 : sympt = A_RBBB  $\vee$  sympt = A_LBBB
    grd3 : d_wave  $\in$   $\mathbb{N}$ 
    grd4 : (d_wave + PR.Int)  $\leq$  120
           Delta_Wave + PR  $\leq$  120 Heart_State = KO
    grd5 : Disease_step4 = Acute_inferior_MI
    grd6 : exmi  $\in$  Mice_State5  $\wedge$  exmi = Exclude_Mimics_MI
  then
    act2 : Delta_Wave := d_wave
    act3 : Disease_step3 := WPW_Syndrome
  end

Event QRS_Test_Atypical_RBBB_Brugada_Syndrome  $\hat{=}$ 
  Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends QRS_Test_Atypical_RBBB_Brugada_Syndrome

  any
    sympt
    dis
  where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int  $\geq$  110
    grd4 : Slurred_S(V5) = FALSE  $\wedge$ 
           Slurred_S(V6) = FALSE
    grd5 : dis  $\in$  Disease_Codes_Step3  $\setminus$  {WPW_Syndrome, NDS3}
    grd6 : ST_elevation(V1) = TRUE  $\wedge$ 
           ST_elevation(V2) = TRUE
    grd7 : Sinus = Yes
  then
    act1 : Disease_step3 := Brugada_Syndrome
  end

Event QRS_Test_Atypical_RBBB_RV_Dysplasia  $\hat{=}$ 
  Right Ventricular Dysplasia

extends QRS_Test_Atypical_RBBB_RV_Dysplasia

  any
    sympt
    dis
  where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int  $\geq$  110
    grd4 : dis  $\in$  Disease_Codes_Step3  $\setminus$  {WPW_Syndrome, Brugada_Syndrome, NDS3}
    grd5 : Epsilon_Wave(V1) = TRUE  $\wedge$ 
           Epsilon_Wave(V3) = TRUE
  then
    act1 : Disease_step3 := RV_Dysplasia
  end
end

```

Event *QRS_Test_Atypical_RBBB_IVCD* $\hat{=}$
IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

dis

where

grd1 : QRS_Int \geq 110

grd2 : dis \in Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, NDS3}

grd3 : Heart_State = KO

then

act1 : Disease_step3 := IVCD

end

Event *ST_seg_elevation_YES* $\hat{=}$
ST segment elevation...

extends *ST_seg_elevation_YES*

when

grd1 : Heart_State = KO

grd2 : Sinus = Yes

grd3 : \vee

$((\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
 $(ST_elevation(l1) = TRUE \wedge ST_elevation(k1) = TRUE)$

\wedge
 $(ST_seg_ele(l1) \geq 1000 \wedge ST_seg_ele(k1) \geq 1000)$
 $\wedge l1 \neq k1$

\wedge
(
 $(l1 = V1 \wedge k1 = V2) \vee$
 $(l1 = V2 \wedge k1 = V3) \vee$
 $(l1 = V3 \wedge k1 = V4) \vee$
 $(l1 = V4 \wedge k1 = V5) \vee$
 $(l1 = V5 \wedge k1 = V6)$
)
)

grd4 : Disease_step4 \in {Acute_inferior_MI, Acute_anterior_MI}

then

act1 : Disease_step4 := STEMI

end

Event *ST_seg_elevation_NOTCKMB_Yes* $\hat{=}$
Troponin or CK-MB positive YES

extends *ST_seg_elevation_NOTCKMB_Yes*

when

grd1 : Heart_State = KO

grd2 : Sinus = Yes

grd3 : \vee

$(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$

$(ST_elevation(l1) = FALSE \wedge ST_seg_ele(l1) < 1000))$

```

grd4 :  $\exists l, k. l \in \text{LEADS} \wedge k \in \text{LEADS} \wedge$ 
       $(\text{ST\_depression}(l) \geq 1000 \wedge \text{ST\_depression}(k) \geq 1000)$ 
       $\wedge l \neq k$ 
grd5 : Disease_step4  $\in$  {Troponin, CK_MB}
  then
    act1 : Disease_step4 := Non_STEMI
  end

Event ST_seg_elevation_NO_TCKMB_No  $\hat{=}$ 
  Troponin or CK-MB positive No

extends ST_seg_elevation_NO_TCKMB_No

  when
    grd1 : Heart.State = KO
    grd2 : Sinus = Yes
    grd3 :  $\vee$ 
       $(\forall l. l \in \{II, III, aVF\} \Rightarrow$ 
         $(\text{ST\_elevation}(l) = \text{FALSE} \wedge \text{ST\_seg\_ele}(l) < 1000))$ 
grd4 :  $\exists l, k. l \in \text{LEADS} \wedge k \in \text{LEADS} \wedge$ 
       $(\text{ST\_depression}(l) \geq 1000 \wedge \text{ST\_depression}(k) \geq 1000)$ 
       $\wedge l \neq k$ 
grd5 : Disease_step4  $\notin$  {Troponin, CK_MB}
  then
    act1 : Disease_step4 := Ischemia
  end

Event Q_Assessment_Normal  $\hat{=}$ 
  Q wave assessment normal

extends Q_Assessment_Normal

  when
    grd1 :  $\text{Q\_Width}(II) < 40 \wedge \text{Q\_Depth}(II) \leq 3000 \wedge$ 
       $\text{Q\_Width}(aVF) < 40 \wedge \text{Q\_Depth}(aVF) \leq 3000 \wedge$ 
       $\text{Q\_Width}(aVL) < 40$ 
      1000 micrometer = 1 millimeter
    grd2 :  $\text{Q\_Width}(III) \leq 40 \wedge \text{Q\_Depth}(III) \leq 7000 \wedge \text{Q\_Depth}(aVL) \leq 7000$ 
    grd3 :  $\text{Q\_Depth}(I) < 40 \wedge \text{Q\_Depth}(I) \leq 1500$ 
  then
    act1 : Q_Normal_Status := TRUE
  end

Event Q_Assessment_Abnormal_AMI  $\hat{=}$ 
  Q wave assessment abnormal for anterolateral MI (AMI)

extends Q_Assessment_Abnormal_AMI

  when
    grd1 : Heart.State = KO
    grd2 : Sinus = Yes

```



```

    grd3 :  $\vee$ 
    (( $\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
    ( $ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE$ )
     $\wedge$ 
    ( $ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000$ )
     $\wedge l1 \neq k1$ 
     $\wedge$ 
    (
    ( $l1 = V1 \wedge k1 = V2$ )  $\vee$ 
    ( $l1 = V2 \wedge k1 = V3$ )  $\vee$ 
    ( $l1 = V3 \wedge k1 = V4$ )  $\vee$ 
    ( $l1 = V4 \wedge k1 = V5$ )  $\vee$ 
    ( $l1 = V5 \wedge k1 = V6$ )
    )
    ))
grd4 :  $Q\_Width(V5) \geq 40 \wedge Q\_Depth(V5) > 3000 \wedge$ 
       $Q\_Width(V6) \geq 40 \wedge Q\_Depth(V6) > 3000$ 
grd5 :  $Q\_Width(aVL) \geq 40 \wedge Q\_Depth(aVL) > 7000$ 
grd6 :  $Q\_Depth(I) \geq 40 \wedge Q\_Depth(I) > 1500$ 
grd7 :  $Q\_Normal\_Status = FALSE$ 
  then
    act1 :  $Disease\_step4 := Acute\_anterior\_MI$ 
  end
Event  $Q\_Assessment\_Abnormal\_IMI \hat{=} Q$ 
  wave assessment abnormal for inferior MI (IMI)
extends  $Q\_Assessment\_Abnormal\_IMI$ 
  when
    grd1 :  $Heart\_State = KO$ 
    grd2 :  $Sinus = Yes$ 
    grd3 :  $\vee$ 
    (( $\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
    ( $ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE$ )
     $\wedge$ 
    ( $ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000$ )
     $\wedge l1 \neq k1$ 
     $\wedge$ 
    (
    ( $l1 = V1 \wedge k1 = V2$ )  $\vee$ 
    ( $l1 = V2 \wedge k1 = V3$ )  $\vee$ 
    ( $l1 = V3 \wedge k1 = V4$ )  $\vee$ 
    ( $l1 = V4 \wedge k1 = V5$ )  $\vee$ 
    ( $l1 = V5 \wedge k1 = V6$ )
    )
    ))
grd4 :  $Q\_Width(II) \geq 40 \wedge Q\_Depth(II) > 3000 \wedge$ 
       $Q\_Width(III) > 40 \wedge Q\_Depth(III) > 7000 \wedge$ 
       $Q\_Width(aVF) \geq 40 \wedge Q\_Depth(aVF) > 3000$ 
grd5 :  $Q\_Normal\_Status = FALSE$ 
  then
    act1 :  $Disease\_step4 := Acute\_inferior\_MI$ 
  end
Event  $Determine\_Age\_of\_Infarct \hat{=} Q$ 

```

```

extends Determine_Age_of_Infarct
  when
    grd1 : Disease_step4 = Acute_inferior_MI
          ∨
          Disease_step5 ∈ {anterior_MI, LVH, emphysema}
          ∨
          Mice_State = Exclude_Mimics_MI
          ∨
          Disease_step2 = LBBB
  then
    act1 : Age_of_Inf ∈ {recent, old, indeterminate}
  end
Event Exclude_Mimics ≐
extends Exclude_Mimics
  any
    exmi
  where
    grd1 : Disease_step4 = Acute_inferior_MI
    grd2 : exmi ∈ Mice_State5 ∧ exmi = Exclude_Mimics_MI
  then
    act1 : Disease_step5 := Hypertrophic_cardiomyopathy
    act2 : Mice_State := borderline_Qs
  end
Event R_Assessment_Normal ≐
  Q wave assessment normal
extends R_Assessment_Normal
  any
    age
  where
    grd1 : R.Depth(V1) ≥ 0 ∧ R.Depth(V1) ≤ 6000 ∧ age > 30
          1000 micrometer = 1 millimeter
    grd2 : R.Depth(V2) > 200 ∧ R.Depth(V2) ≤ 12000
    grd3 : R.Depth(V2) ≥ 1000 ∧ R.Depth(V2) ≤ 24000
  then
    act1 : R.Normal_Status := TRUE
  end
Event R_Assessment_Abnormal ≐
extends R_Assessment_Abnormal
  when
    grd1 : R.Normal_Status = FALSE
  then
    act1 : Mice_State ∈ {late_transition, normal_variant}
  end

```

Event *R_Q_Assessment_R_Abnormal_V1234* $\hat{=}$
R wave abnormal , pathologic Q waves consider in V1-V4

extends *R_Q_Assessment_R_Abnormal_V1234*

when

grd1 : R.Normal_Status = FALSE
grd2 : Q_Wave_State(V1) = TRUE \wedge
 Q_Wave_State(V2) = TRUE \wedge
 Q_Wave_State(V3) = TRUE \wedge
 Q_Wave_State(V4) = TRUE
grd3 : Heart_State = KO

then

act1 : Disease_step5 \in {anterior_MI, LVH, emphysema}
act2 : Mice_State := Exclude_Mimics_MI

end

Event *R_Q_Assessment_R_Abnormal_V56* $\hat{=}$

R wave abnormal , pathologic Q waves consider in V5-V6

extends *R_Q_Assessment_R_Abnormal_V56*

when

grd1 : Q_Wave_State(V5) = TRUE \wedge
 Q_Wave_State(V6) = TRUE
grd3 : Heart_State = KO

then

act1 : Disease_step5 \in {lateral_MI, Hypertrophic_cardiomyopathy}

end

Event *P_Wave_assessment_Peaked_Broad_No* $\hat{=}$

extends *P_Wave_assessment_Peaked_Broad_No*

when

grd1 : (P_Wave_Peak(II) < 3000 \wedge
 P_Wave_Peak(V1) < 3000)
 \vee
 (P_Wave_Broad(II) < 110 \wedge P_Wave_Broad(V1) < 110) \vee
 Diphasic(II) = FALSE \vee
 Diphasic(V1) = FALSE

then

act1 : Disease_step6 := NDS6

end

Event *P_Wave_assessment_Peaked_Yes* $\hat{=}$

extends *P_Wave_assessment_Peaked_Yes*

when

grd1 : P_Wave_Peak(II) \geq 3000
grd2 : P_Wave_Peak(V1) \geq 3000
grd3 : Heart_State = KO

then

act1 : Disease_step6 := RAE

```

    end

Event P_Wave_assessment_Peaked_Yes_Check_RAE  $\hat{=}$ 
refines P_Wave_assessment_Peaked_Yes_Check_RAE

    when
        grd1 : P_Wave_Peak(II)  $\geq 3000$ 
        grd2 : P_Wave_Peak(V1)  $\geq 3000$ 
        grd3 : Disease_step6 = RAE
        grd4 : Heart_State = KO
    then
        act1 : Disease_step6  $\in$  {RV_strain, pulmonary_embolism}
    end

Event P_Wave_assessment_Broad_Yes  $\hat{=}$ 
extends P_Wave_assessment_Broad_Yes

    when
        grd1 : (P_Wave_Broad(II)  $\geq 110$   $\wedge$  P_Wave_Broad(V1)  $\geq 110$ )  $\vee$ 
            Diphasic(II) = TRUE  $\vee$ 
            Diphasic(V1) = TRUE
        grd2 : Heart_State = KO
    then
        act1 : Disease_step6 := LAE
    end

Event P_Wave_assessment_Broad_Yes_Check_LAE  $\hat{=}$ 
refines P_Wave_assessment_Broad_Yes_Check_LAE

    when
        grd1 : (P_Wave_Broad(II)  $\geq 110$   $\wedge$  P_Wave_Broad(V1)  $\geq 110$ )  $\vee$ 
            Diphasic(II) = TRUE  $\vee$ 
            Diphasic(V1) = TRUE
        grd2 : Disease_step6 = LAE
        grd3 : Heart_State = KO
    then
        act1 : Disease_step6  $\in$  {mitral_stenosis, mitral_regurgitation, LV_failure, dilated_cardiomyopathy}
    end

Event LVH_Assessment  $\hat{=}$ 
    LVH_Assessment

refines P_Wave_assessment_Broad_Yes_Check_LAE

    any
        LVH_specificity    specificity in percentage
        sensitivity        sensitivity in percentage
        sex
    where
        grd1 : (P_Wave_Broad(II)  $\geq 110$   $\wedge$  P_Wave_Broad(V1)  $\geq 110$ )  $\vee$ 
            Diphasic(II) = TRUE  $\vee$ 
            Diphasic(V1) = TRUE

```

```

grd2 : Disease_step6 = LAE
grd5 : sex ∈ {0, 1}
      o for men and 1 for women
grd3 : ((S_Depth(V1) + R_Depth(V5)) > 35000
      ∨
      (S_Depth(V1) + R_Depth(V6)) > 35000)
      1mm = 1000 micrometer..... 1 assessment
grd4 : ((R_Depth(aVL) + S_Depth(V1) ≥ 24000) ∧ sex = 0)
      ∨
      ((R_Depth(aVL) + S_Depth(V1) ≥ 18000) ∧ sex = 1)
      2 assessment
grd6 : LVH_specificity = 90
      ∧
      sensitivity < 40
      1 and 2 assessment
grd7 : Disease_step6 = LAE ⇒ LVH_specificity < 98
      3 assessment
grd8 : Heart_State = KO
then
  act1 : Disease_step6 := LVH_cause
end
Event RVH_Assessment ≐
RVH_Assessment
refines P_Wave_assessment_Peaked_Yes_Check_RAE
any
  age    age of men or women
  aixs   axis for deviation
where
grd1 : P_Wave_Peak(II) ≥ 3000
grd2 : P_Wave_Peak(V1) ≥ 3000
grd3 : Disease_step6 = RAE
grd4 : R_Depth(V1) ≥ 7000 ∧ age > 30
      1 assessment
grd5 : S_Depth(V5) ≥ 7000 ∨
      S_Depth(V6) ≥ 7000
      2 assessment
grd6 : R_S_Ratio(V1) ≥ 100
      R.S Ratio is multiply by 100 to remove the real no. constants... 3 assessment
grd7 : R_S_Ratio(V5) ≤ 100
      ∨
      R_S_Ratio(V6) ≤ 100
      4 assessment
grd8 : aixs ∈ 0 .. 360 ∧ aixs ≥ 110
      5 assessment
grd9 : Disease_step2 ∉ {LBBB, RBBB}
grd10 : QRS_Int < 120
grd11 : Heart_State = KO
then
  act1 : Disease_step6 := RVH
end
END

```

CONTEXT Step8_ctx

SETS

T_State
Disease_Codes_Step8
T_State_B
T_State_l_d
Disease_states_Codes_step8B

CONSTANTS

Peaked
Flat
Inverted
Hyperkalemia
posterior_MI
Nonspecific_ST_T_changes
Nonspecific
Definite_ischemia
Probable_ischemia
Digitalis_effect
NDS8
Upright
Inverted_B
Variable
Localized
Diffuse
Cardiomyopathy
other_nonspecific
Electrolyte_depletion
Alcohol
Myocarditis
Other
NDS8B

AXIOMS

axm1: $T_State = \{Peaked, Flat, Inverted\}$
axm2: $\neg Peaked = Flat$
axm3: $\neg Peaked = Inverted$
axm4: $\neg Flat = Inverted$
axm5: $Disease_Codes_Step8 = \{Hyperkalemia, posterior_MI, Nonspecific_ST_T_changes, Nonspecific, Definite_ischemia, Probable_ischemia, Digitalis_effect, NDS8\}$
axm6: $\neg Hyperkalemia = posterior_MI$
axm7: $\neg Hyperkalemia = Nonspecific_ST_T_changes$

axm8 : \neg Hyperkalemia = Nonspecific
 axm9 : \neg Hyperkalemia = Definite_ischemia
 axm10 : \neg Hyperkalemia = Probable_ischemia
 axm11 : \neg Hyperkalemia = Digitalis_effect
 axm12 : \neg Hyperkalemia = NDS8
 axm13 : \neg posterior_MI = Nonspecific_ST_T_changes
 axm14 : \neg posterior_MI = Nonspecific
 axm15 : \neg posterior_MI = Definite_ischemia
 axm16 : \neg posterior_MI = Probable_ischemia
 axm17 : \neg posterior_MI = Digitalis_effect
 axm18 : \neg posterior_MI = NDS8
 axm19 : \neg Nonspecific_ST_T_changes = Nonspecific
 axm20 : \neg Nonspecific_ST_T_changes = Definite_ischemia
 axm21 : \neg Nonspecific_ST_T_changes = Probable_ischemia
 axm22 : \neg Nonspecific_ST_T_changes = Digitalis_effect
 axm23 : \neg Nonspecific_ST_T_changes = NDS8
 axm24 : \neg Nonspecific = Definite_ischemia
 axm25 : \neg Nonspecific = Probable_ischemia
 axm26 : \neg Nonspecific = Digitalis_effect
 axm27 : \neg Nonspecific = NDS8
 axm28 : \neg Definite_ischemia = Probable_ischemia
 axm29 : \neg Definite_ischemia = Digitalis_effect
 axm30 : \neg Definite_ischemia = NDS8
 axm31 : \neg Probable_ischemia = Digitalis_effect
 axm32 : \neg Probable_ischemia = NDS8
 axm33 : \neg Digitalis_effect = NDS8
 axm34 : $T_State_B = \{Upright, Inverted_B, Variable\}$
 axm35 : $\neg Upright = Inverted_B$
 axm36 : $\neg Upright = Variable$
 axm37 : $\neg Inverted_B = Variable$
 axm38 : $T_State_l_d = \{Localized, Diffuse\}$
 axm39 : $\neg Localized = Diffuse$
 axm40 : $Disease_states_Codes_step8B = \{Cardiomyopathy, other_nonspecific, Electrolyte_depletion, Alcohol, Myocarditis, Other, NDS8B\}$
 axm41 : $\neg Cardiomyopathy = other_nonspecific$
 axm42 : $\neg Cardiomyopathy = Electrolyte_depletion$
 axm43 : $\neg Cardiomyopathy = Alcohol$
 axm44 : $\neg Cardiomyopathy = Myocarditis$
 axm45 : $\neg Cardiomyopathy = Other$
 axm46 : $\neg Cardiomyopathy = NDS8B$
 axm47 : $\neg other_nonspecific = Electrolyte_depletion$
 axm48 : $\neg other_nonspecific = Alcohol$
 axm49 : $\neg other_nonspecific = Myocarditis$
 axm50 : $\neg other_nonspecific = Other$

axm51 : \neg other_nonspecific = NDS8B
axm52 : \neg Electrolyte_depletion = Alcohol
axm53 : \neg Electrolyte_depletion = Myocarditis
axm54 : \neg Electrolyte_depletion = Other
axm55 : \neg Electrolyte_depletion = NDS8B
axm56 : \neg Alcohol = Myocarditis
axm57 : \neg Alcohol = Other
axm58 : \neg Alcohol = NDS8B
axm59 : \neg Myocarditis = Other
axm60 : \neg Myocarditis = NDS8B
axm61 : \neg Other = NDS8B

END

An Event-B Specification of Step8
Generated Date: 25 Nov 2010 @ 03:39:35 PM

MACHINE Step8

REFINES Step7_LVH_RVH

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx, Step8_ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
Small_R_QS A small R or QS wave in V1 and V2
Slurred_S_duration Slurred S duration
Delta_Wave Delta Wave
Disease_step3
ST_elevation ST segment elevation (Coved or Saddle-back)
Epsilon_Wave Epsilon Wave or (a terminal notch in the QRS)
ST_seg_ele ST segment for elevation 1mm=0.1mV
Disease_step4
Q_Width Q wave width
Q_Depth Q wave depth
Q_Normal_Status Q wave normal or abnormal
Age_of_Inf Age of Infarct
Disease_step5
Mice_State
PP_Interval
RR_Interval
R_Depth R wave depth or height (also use in Step 7)
R_Normal_Status R wave normal or abnormal
Q_Wave_State Q wave states for all LEADS
P_Wave_Peak function to estimate the peak of LEADS signal
Disease_step6
Diphasic
P_Wave_Broad
S_Depth S wave depth or height

R_S_Ratio R wave and S wave Ratio function
T_Wave_State T wave patterns...
Disease_step8
ST_depression

INVARIANTS

inv1 : $T_Wave_State \in LEADS \rightarrow T_State$
inv2 : $Disease_step8 \in Disease_Codes_Step8$
inv3 : $Sinus = Yes \wedge Disease_step8 = Nonspecific \Rightarrow Heart_State = KO$
inv4 : $Sinus = Yes \wedge Disease_step8 = Nonspecific_ST_T_changes \Rightarrow Heart_State = KO$
inv5 : $Sinus = Yes \wedge Disease_step8 = posterior_MI \Rightarrow Heart_State = KO$
inv6 : $Sinus = Yes \wedge Disease_step8 \in \{Definite_ischemia, Probable_ischemia, Digitalis_effect\} \Rightarrow Heart_State = KO$

EVENTS

Initialisation

extended

begin

act1 : $RR_Int_equidistant : \in LEADS \rightarrow BOOL$
act2 : $PP_Int_equidistant : \in LEADS \rightarrow BOOL$
act3 : $P_Positive : \in LEADS \rightarrow BOOL$
act4 : $Sinus := No$
act5 : $PP_Interval : \in LEADS \rightarrow \mathbb{N}$
act6 : $RR_Interval : \in LEADS \rightarrow \mathbb{N}$
act7 : $Heart_Rate : \in 1..300$
act8 : $Heart_State := KO$
act9 : $PR_Int := 120$
act10 : $Disease_step2 := NDS2$
act11 : $QRS_Int := 50$
act12 : $Notched_R : \in LEADS \rightarrow BOOL$
act13 : $Small_R_QS : \in LEADS \rightarrow BOOL$
act14 : $Slurred_S_duration : \in LEADS \rightarrow \mathbb{N}_1$
act15 : $M_Shape_Complex : \in LEADS \rightarrow BOOL$
act16 : $Slurred_S : \in LEADS \rightarrow BOOL$
act17 : $ST_elevation : \in LEADS \rightarrow BOOL$
act18 : $Epsilon_Wave : \in LEADS \rightarrow BOOL$
act19 : $Delta_Wave := 0$
act20 : $Disease_step3 := NDS3$
act21 : $ST_seg_ele : \in LEADS \rightarrow \mathbb{N}$
act22 : $Disease_step4 := NDS4$
act57 : $ST_depression : \in LEADS \rightarrow \mathbb{N}$
act23 : $Q_Width : \in LEADS \rightarrow \mathbb{N}$
act24 : $Q_Depth : \in LEADS \rightarrow \mathbb{N}$
act25 : $Q_Normal_Status := FALSE$
act26 : $Mice_State := NMS$
act27 : $R_Depth : \in LEADS \rightarrow \mathbb{N}$
act28 : $R_Normal_Status := FALSE$
act29 : $Q_Wave_State : \in LEADS \rightarrow BOOL$
act30 : $Age_of_Inf : \in Age_of_Infarct$

```

act31 : Disease_step5 := NDS5
act32 : Diphasic :∈ LEADS → BOOL
act33 : P_Wave_Broad :∈ LEADS → ℕ
act34 : P_Wave_Peak :∈ LEADS → ℕ
act35 : Disease_step6 := NDS6
act36 : S_Depth :∈ LEADS → ℕ
act37 : R_S_Ratio :∈ LEADS → ℕ
act38 : T_Wave_State :∈ LEADS → T_State
act39 : Disease_step8 := NDS8

end

Event Rhythm_test.TRUE ≐
  Sinus Rhythm with Normal Rate

extends Rhythm_test.TRUE

any
  rate
where
  grd1 : (∃l.l ∈ {II, V1, V2} ∧ PP_Int.equidistant(l) = TRUE ∧
    RR_Int.equidistant(l) = TRUE ∧
    RR_Interval(l) = PP_Interval(l))
    ∧
    P_Positive(II) = TRUE
  grd4 : rate ∈ 60..100
    60..100 is the range of normal heart rate
  grd5 : PR_Int ≤ 200
    Heart is Normal if PR ≤ 200 QRS_Int < 120
    HeartisNormalifQRS < 120
  grd6grd7 : Disease_step2 = NDS2
  grd8 : Disease_step3 = NDS3
  grd9 : Disease_step4 = NDS4
  grd10 : Disease_step5 = NDS5
  grd11 : Disease_step6 = NDS6
  grd12 : Disease_step8 = NDS8

then
  act1 : Sinus := Yes
  act2 : Heart_Rate := rate
  act3 : Heart_State := OK

end

Event Rhythm_test.FALSE ≐
  Abnormal Rhythm with Rate

extends Rhythm_test.FALSE

any
  rate
where
  grd1 : (∀l.l ∈ {II, V1, V2} ⇒ PP_Int.equidistant(l) = FALSE ∨
    RR_Int.equidistant(l) = FALSE ∨
    RR_Interval(l) ≠ PP_Interval(l))
    ∨
    P_Positive(II) = FALSE

```

```

    grd2 : rate ∈ 1 .. 300
  then
    act1 : Sinus := No
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end
Event Rhythm_test.TRUE_Rate ≐
  Sinus Rhythm with abnormal Rate
extends Rhythm_test.TRUE_Rate
  any
    rate
  where
    grd1 : (∃l·l ∈ {II, V1, V2} ∧ PP_Int.equidistant(l) = TRUE ∧
      RR_Int.equidistant(l) = TRUE ∧
      RR.Interval(l) = PP.Interval(l))
      ∧
      P_Positive(II) = TRUE
    grd5 : rate ∈ 1 .. 300 \ 60 .. 100
      60..100 is the range of normal heart rate, so rest of no. is abnormal
    grd6 : Disease_step3 = WPW.Syndrome ∨ Disease_step3 = Brugada.Syndrome ∨
      Disease_step3 = RV_Dysplasia ∨ Disease_step3 = IVCD
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end
Event PR_Test ≐
  PR Interval Test
extends PR_Test
  any
    pr
  where
    grd1 : pr ∈ 120 .. 220
      time interval in (ms.)
    grd2 : pr > 200
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
  then
    act1 : PR.Int := pr
    act2 : Disease_step2 := First_degree_AV_Block
  end
Event QRS_Test_LBBB ≐
  QRS Complex Interval Test
extends QRS_Test_LBBB
  any

```

```

    qrs
  where
    grd1 : qrs ∈ 50 .. 150
    grd2 : qrs ≥ 120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : Notched_R(I) = TRUE ∧
           Notched_R(V5) = TRUE ∧
           Notched_R(V6) = TRUE
           Right Bundle Branch Block (RBBB)
    grd6 : Small_R_QS(V1) = TRUE ∧
           Small_R_QS(V2) = TRUE
    grd7 : Q_Wave_State(V1) = TRUE ∧
           Q_Wave_State(V2) = TRUE ∧
           Q_Wave_State(V3) = TRUE ∧
           Q_Wave_State(V4) = TRUE
           from step 5
    grd8 : R_Normal_Status = FALSE
           from step 5
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := LBBB
  end
Event QRS_Test_RBBB ≐
  Right Bundle Branch Block (RBBB)
extends QRS_Test_RBBB
any
  qrs
  where
    grd1 : qrs ∈ 50 .. 150
    grd2 : qrs ≥ 120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : M_Shape_Complex(V1) = TRUE ∧
           M_Shape_Complex(V2) = TRUE
    grd7 : Slurred_S(I) = TRUE ∧
           Slurred_S(V5) = TRUE ∧
           Slurred_S(V6) = TRUE
    grd8 : Slurred_S_duration(I) > 40 ∧
           Slurred_S_duration(V5) > 40 ∧
           Slurred_S_duration(V6) > 40
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := RBBB
  end
end
Event QRS_Test_Atypical_RLBBB_WPW_Syndrome ≐
  QRS Test for Atypical LBBB RBBB
extends QRS_Test_Atypical_RLBBB_WPW_Syndrome

```

```

any
  sympt
  d_wave
  exmi
where
  grd1 : QRS_Int ≥ 110
  grd2 : sympt = A_RBBB ∨ sympt = A_LBBB
  grd3 : d_wave ∈ ℕ
  grd4 : (d_wave + PR_Int) ≤ 120
          Delta_Wave + PR ≤ 120 Heart_State = KO
  grd5 : Disease_step4 = Acute_inferior_MI
  grd6 : Disease_step4 = Acute_inferior_MI
  grd7 : exmi ∈ Mice_State5 ∧ exmi = Exclude_Mimics_MI
then
  act2 : Delta_Wave := d_wave
  act3 : Disease_step3 := WPW_Syndrome
end

Event QRS_Test_Atypical_RBBB_Brugada_Syndrome ≐
  Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends QRS_Test_Atypical_RBBB_Brugada_Syndrome

any
  sympt
  dis
where
  grd1 : sympt = A_RBBB
  grd2 : Heart_State = KO
  grd3 : QRS_Int ≥ 110
  grd4 : Slurred_S(V5) = FALSE ∧
          Slurred_S(V6) = FALSE
  grd5 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, NDS3}
  grd6 : ST_elevation(V1) = TRUE ∧
          ST_elevation(V2) = TRUE
  grd7 : Sinus = Yes
then
  act1 : Disease_step3 := Brugada_Syndrome
end

Event QRS_Test_Atypical_RBBB_RV_Dysplasia ≐
  Right Ventricular Dysplasia

extends QRS_Test_Atypical_RBBB_RV_Dysplasia

any
  sympt
  dis
where
  grd1 : sympt = A_RBBB
  grd2 : Heart_State = KO
  grd3 : QRS_Int ≥ 110
  grd4 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, NDS3}

```

```

    grd5 : Epsilon_Wave(V1) = TRUE ∧
           Epsilon_Wave(V3) = TRUE
  then
    act1 : Disease_step3 := RV_Dysplasia
  end

Event QRS_Test_Atypical_RBBB_IVCD  $\hat{=}$ 
  IVCD diagnosis

extends QRS_Test_Atypical_RBBB_IVCD

  any
    dis
  where
    grd1 : QRS_Int  $\geq$  110
    grd2 : dis  $\in$  Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, NDS3}
    grd3 : Heart_State = KO
  then
    act1 : Disease_step3 := IVCD
  end

Event ST_seg_elevation_YES  $\hat{=}$ 
  ST segment elevation...

extends ST_seg_elevation_YES

  when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :
       $\vee$ 
      (( $\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
      (ST_elevation(l1) = TRUE  $\wedge$  ST_elevation(k1) = TRUE)
       $\wedge$ 
      (ST_seg_ele(l1)  $\geq$  1000  $\wedge$  ST_seg_ele(k1)  $\geq$  1000)
       $\wedge$  l1  $\neq$  k1
       $\wedge$ 
      (
        (l1 = V1  $\wedge$  k1 = V2)  $\vee$ 
        (l1 = V2  $\wedge$  k1 = V3)  $\vee$ 
        (l1 = V3  $\wedge$  k1 = V4)  $\vee$ 
        (l1 = V4  $\wedge$  k1 = V5)  $\vee$ 
        (l1 = V5  $\wedge$  k1 = V6)
      )
    ))
  grd4 : Disease_step4  $\in$  {Acute_inferior_MI, Acute_anterior_MI}
  then
    act1 : Disease_step4 := STEMI
  end

Event ST_seg_elevation_NOTCKMB_Yes  $\hat{=}$ 
  Troponin or CK-MB positive YES

extends ST_seg_elevation_NOTCKMB_Yes

  when

```

```

    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :          ∨
    (∀l1·l1 ∈ {II, III, aVF} ⇒
    (ST_elevation(l1) = FALSE ∧ ST_seg_ele(l1) < 1000))
grd4 : ∃l, k·l ∈ LEADS ∧ k ∈ LEADS ∧
    (ST_depression(l) ≥ 1000 ∧ ST_depression(k) ≥ 1000
    ∧ l ≠ k
grd5 : Disease_step4 ∈ {Troponin, CK_MB}
    then
        act1 : Disease_step4 := Non_STEMI
    end
Event ST_seg_elevation_NO_TCKMB_No ≐
    Troponin or CK-MB positive No
extends ST_seg_elevation_NO_TCKMB_No
    when
        grd1 : Heart_State = KO
        grd2 : Sinus = Yes
        grd3 :          ∨
        (∀l1·l1 ∈ {II, III, aVF} ⇒
        (ST_elevation(l1) = FALSE ∧ ST_seg_ele(l1) < 1000))
grd4 : ∃l, k·l ∈ LEADS ∧ k ∈ LEADS ∧
    (ST_depression(l) ≥ 1000 ∧ ST_depression(k) ≥ 1000
    ∧ l ≠ k
grd5 : Disease_step4 ∉ {Troponin, CK_MB}
    then
        act1 : Disease_step4 := Ischemia
    end
Event Q_Assessment_Normal ≐
    Q wave assessment normal
extends Q_Assessment_Normal
    when
        grd1 : Q_Width(II) < 40 ∧ Q_Depth(II) ≤ 3000 ∧
            Q_Width(aVF) < 40 ∧ Q_Depth(aVF) ≤ 3000 ∧
            Q_Width(aVL) < 40
            1000 micrometer = 1 millimeter
        grd2 : Q_Width(III) ≤ 40 ∧ Q_Depth(III) ≤ 7000 ∧ Q_Depth(aVL) ≤ 7000
        grd3 : Q_Depth(I) < 40 ∧ Q_Depth(I) ≤ 1500
    then
        act1 : Q_Normal_Status := TRUE
    end
Event Q_Assessment_Abnormal_AMI ≐
    Q wave assessment abnormal for anterolateral MI (AMI)
extends Q_Assessment_Abnormal_AMI
    when
        grd1 : Heart_State = KO

```



```

    grd2 : Sinus = Yes
    grd3 :          ∨
    ((∃l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
    (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
    ∧
    (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
    ∧ l1 ≠ k1
    ∧
    (
    (l1 = V1 ∧ k1 = V2) ∨
    (l1 = V2 ∧ k1 = V3) ∨
    (l1 = V3 ∧ k1 = V4) ∨
    (l1 = V4 ∧ k1 = V5) ∨
    (l1 = V5 ∧ k1 = V6)
    )
    ))
grd4 : Q_Width(V5) ≥ 40 ∧ Q_Depth(V5) > 3000 ∧
      Q_Width(V6) ≥ 40 ∧ Q_Depth(V6) > 3000
grd5 : Q_Width(aVL) ≥ 40 ∧ Q_Depth(aVL) > 7000
grd6 : Q_Depth(I) ≥ 40 ∧ Q_Depth(I) > 1500
grd7 : Q_Normal_Status = FALSE
  then
    act1 : Disease_step4 := Acute_anterior_MI
  end

Event Q_Assessment_Abnormal_IMI ≐
  Q_wave_assessment_abnormal_for_inferior_MI (IMI)

extends Q_Assessment_Abnormal_IMI

  when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :          ∨
    ((∃l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
    (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
    ∧
    (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
    ∧ l1 ≠ k1
    ∧
    (
    (l1 = V1 ∧ k1 = V2) ∨
    (l1 = V2 ∧ k1 = V3) ∨
    (l1 = V3 ∧ k1 = V4) ∨
    (l1 = V4 ∧ k1 = V5) ∨
    (l1 = V5 ∧ k1 = V6)
    )
    ))
grd4 : Q_Width(II) ≥ 40 ∧ Q_Depth(II) > 3000 ∧
      Q_Width(III) > 40 ∧ Q_Depth(III) > 7000 ∧
      Q_Width(aVF) ≥ 40 ∧ Q_Depth(aVF) > 3000
grd5 : Q_Normal_Status = FALSE
  then
    act1 : Disease_step4 := Acute_inferior_MI
  end

```

```

Event Determine_Age_of_Infarct  $\hat{=}$ 
extends Determine_Age_of_Infarct
  when
    grd1 : Disease_step4 = Acute_inferior_MI
           $\vee$ 
          Disease_step5  $\in$  {anterior_MI, LVH, emphysema}
           $\vee$ 
          Mice_State = Exclude_Mimics_MI
           $\vee$ 
          Disease_step2 = LBBB
  then
    act1 : Age_of_Inf  $:\in$  {recent, old, indeterminate}
  end

Event Exclude_Mimics  $\hat{=}$ 
extends Exclude_Mimics
  any
    exmi
  where
    grd1 : Disease_step4 = Acute_inferior_MI
    grd2 : exmi  $\in$  Mice_State5  $\wedge$  exmi = Exclude_Mimics_MI
  then
    act1 : Disease_step5 := Hypertrophic_cardiomyopathy
    act2 : Mice_State := borderline_Qs
  end

Event R_Assessment_Normal  $\hat{=}$ 
  Q wave assessment normal
extends R_Assessment_Normal
  any
    age
  where
    grd1 : R.Depth(V1)  $\geq$  0  $\wedge$  R.Depth(V1)  $\leq$  6000  $\wedge$  age > 30
           1000 micrometer = 1 millimeter
    grd2 : R.Depth(V2) > 200  $\wedge$  R.Depth(V2)  $\leq$  12000
    grd3 : R.Depth(V2)  $\geq$  1000  $\wedge$  R.Depth(V2)  $\leq$  24000
  then
    act1 : R.Normal_Status := TRUE
  end

Event R_Assessment_Abnormal  $\hat{=}$ 
extends R_Assessment_Abnormal
  when
    grd1 : R.Normal_Status = FALSE
  then
    act1 : Mice_State  $:\in$  {late_transition, normal_variant}

```

```

end

Event R_Q_Assessment_R_Abnormal_V1234 ≐
  R wave abnormal , pathologic Q waves consider in V1-V4

extends R_Q_Assessment_R_Abnormal_V1234

when
  grd1 : R.Normal_Status = FALSE
  grd2 : Q_Wave_State(V1) = TRUE ∧
        Q_Wave_State(V2) = TRUE ∧
        Q_Wave_State(V3) = TRUE ∧
        Q_Wave_State(V4) = TRUE
  grd3 : Heart_State = KO
then
  act1 : Disease_step5 := {anterior_MI, LVH, emphysema}
  act2 : Mice_State := Exclude_Mimics_MI
end

Event R_Q_Assessment_R_Abnormal_V56 ≐
  R wave abnormal , pathologic Q waves consider in V5-V6

extends R_Q_Assessment_R_Abnormal_V56

when
  grd1 : Q_Wave_State(V5) = TRUE ∧
        Q_Wave_State(V6) = TRUE
  grd3 : Heart_State = KO
then
  act1 : Disease_step5 := {lateral_MI, Hypertrophic_cardiomyopathy}
end

Event P_Wave_assessment_Peaked_Broad_No ≐

extends P_Wave_assessment_Peaked_Broad_No

when
  grd1 : (P_Wave_Peak(II) < 3000 ∧
        P_Wave_Peak(V1) < 3000)
        ∨
        (P_Wave_Broad(II) < 110 ∧ P_Wave_Broad(V1) < 110) ∨
        Diphasic(II) = FALSE ∨
        Diphasic(V1) = FALSE
then
  act1 : Disease_step6 := NDS6
end

Event P_Wave_assessment_Peaked_Yes ≐

extends P_Wave_assessment_Peaked_Yes

when
  grd1 : P_Wave_Peak(II) ≥ 3000
  grd2 : P_Wave_Peak(V1) ≥ 3000
  grd3 : Heart_State = KO
then

```

```

    act1 : Disease_step6 := RAE
  end
Event P_Wave_assessment_Peaked_Yes_Check_RAE  $\hat{=}$ 
refines P_Wave_assessment_Peaked_Yes_Check_RAE
  when
    grd1 : P_Wave_Peak(II)  $\geq$  3000
    grd2 : P_Wave_Peak(V1)  $\geq$  3000
    grd3 : Disease_step6 = RAE
    grd4 : Heart_State = KO
  then
    act1 : Disease_step6 := RV_strain
  end
Event P_Wave_assessment_Broad_Yes  $\hat{=}$ 
extends P_Wave_assessment_Broad_Yes
  when
    grd1 : (P_Wave_Broad(II)  $\geq$  110  $\wedge$  P.Wave_Broad(V1)  $\geq$  110)  $\vee$ 
      Diphasic(II) = TRUE  $\vee$ 
      Diphasic(V1) = TRUE
    grd2 : Heart_State = KO
  then
    act1 : Disease_step6 := LAE
  end
Event P_Wave_assessment_Broad_Yes_Check_LAE  $\hat{=}$ 
extends P_Wave_assessment_Broad_Yes_Check_LAE
  when
    grd1 : (P_Wave_Broad(II)  $\geq$  110  $\wedge$  P.Wave_Broad(V1)  $\geq$  110)  $\vee$ 
      Diphasic(II) = TRUE  $\vee$ 
      Diphasic(V1) = TRUE
    grd2 : Disease_step6 = LAE
    grd3 : Heart_State = KO
  then
    act1 : Disease_step6  $\in$  {mitral_stenosis, mitral_regurgitation, LV_failure,
      dilated_cardiomyopathy}
  end
Event LVH_Assessment  $\hat{=}$ 
  LVH_Assessment
refines LVH_Assessment
  any
    LVH_specificity    specificity in percentage
    sensitivity        sensitivity in percentage
    sex
  where

```

grd1 : $(P_Wave_Broad(II) \geq 110 \wedge P_Wave_Broad(V1) \geq 110) \vee$
 $Diphasic(II) = TRUE \vee$
 $Diphasic(V1) = TRUE$
grd2 : $Disease_step6 = LAE$
grd5 : $sex \in \{0, 1\}$
o for men and 1 for women
grd3 : $((S_Depth(V1) + R_Depth(V5)) > 35000$
 \vee
 $(S_Depth(V1) + R_Depth(V6)) > 35000)$
1mm = 1000 micrometer..... 1 assessment
grd4 : $((R_Depth(aVL) + S_Depth(V1) \geq 24000) \wedge sex = 0)$
 \vee
 $((R_Depth(aVL) + S_Depth(V1) \geq 18000) \wedge sex = 1)$
2 assessment
grd6 : $LVH_specificity = 90$
 \wedge
 $sensitivity < 40$
1 and 2 assessment
grd7 : $Disease_step6 = LAE \Rightarrow LVH_specificity < 98$
3 assessment
grd8 : $Heart_State = KO$
grd9 : $(\forall t \cdot t \in LEADS \Rightarrow ST_elevation(t) = TRUE$
 \vee
 $Q_Normal_Status = FALSE))$
A : from step 8 development

then

act1 : $Disease_step6 := LVH_cause$

end

Event $RVH_Assessment \hat{=}$
RVH Assessment

refines $RVH_Assessment$

any

age age of men or women
aixs axis for deviation

where

grd1 : $P_Wave_Peak(II) \geq 3000$
grd2 : $P_Wave_Peak(V1) \geq 3000$
grd3 : $Disease_step6 = RAE$
grd4 : $R_Depth(V1) \geq 7000 \wedge age > 30$
1 assessment
grd5 : $S_Depth(V5) \geq 7000 \vee$
 $S_Depth(V6) \geq 7000$
2 assessment
grd6 : $R_S_Ratio(V1) \geq 100$
R.S Ratio is multiply by 100 to remove the real no. constants... 3 assessment
grd7 : $R_S_Ratio(V5) \leq 100$
 \vee
 $R_S_Ratio(V6) \leq 100$
4 assessment
grd8 : $aixs \in 0 .. 360 \wedge aixs \geq 110$
5 assessment

```

    grd9 : Disease_step2  $\notin$  {LBBB, RBBB}
    grd10 : QRS_Int < 120
    grd11 : Heart_State = KO
    grd12 : ( $\forall t.t \in$  LEADS  $\Rightarrow$  ST_elevation(t) = TRUE
             $\vee$ 
            Q_Normal_Status = FALSE))
    A : from step 8 development
  then
    act1 : Disease_step6 := RVH
  end
Event T_Wave_Assessment_Peaked_V123456  $\hat{=}$ 
  T Wave Assessment
  when
    grd1 : Heart_State = KO
    grd2 :  $\forall l.l \in$  {V1, V2, V3, V4, V5, V6}  $\Rightarrow$  T_Wave_State(l) = Peaked
  then
    act1 : Disease_step8 := Hyperkalemia
  end
Event T_Wave_Assessment_Peaked_V12  $\hat{=}$ 
refines R_Assessment_Abnormal
  when
    grd1 : R_Normal_Status = FALSE
    grd2 : T_Wave_State(V1) = Peaked  $\wedge$ 
           T_Wave_State(V2) = Peaked
  then
    act1 : Mice_State := normal_variant
  end
Event T_Wave_Assessment_Peaked_V12_MI  $\hat{=}$ 
  posterior MI using T wave assessment in LEADS V1 and V2
  when
    grd1 : T_Wave_State(V1) = Peaked  $\wedge$ 
           T_Wave_State(V2) = Peaked
    grd2 : Heart_State = KO
  then
    act1 : Disease_step8 := posterior_MI
  end
Event T_Wave_Assessment_Flat  $\hat{=}$ 
  when
    grd1 :  $\forall l.l \in$  LEADS  $\Rightarrow$  T_Wave_State(l) = Flat
    grd2 : Heart_State = KO
  then
    act1 : Disease_step8 := Nonspecific_ST_T_changes
  end
Event T_Wave_Assessment_Inverted_Yes  $\hat{=}$ 

```

```

when
  grd1 :  $\forall l \cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$ 
  grd2 :  $\forall l \cdot l \in LEADS \Rightarrow ST\_elevation(l) = TRUE$ 
         $\vee$ 
         $Q\_Normal\_Status = FALSE$ 
  grd3 :  $Heart\_State = KO$ 
then
  act1 :  $Disease\_step8 \in \{Definite\_ischemia, Probable\_ischemia, Digitalis\_effect\}$ 
end

Event  $T\_Wave\_Assessment\_Inverted\_No \hat{=}$ 
when
  grd1 :  $\forall l \cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$ 
  grd2 :  $\forall l \cdot l \in LEADS \Rightarrow ST\_elevation(l) = FALSE$ 
         $\vee$ 
         $Q\_Normal\_Status = TRUE$ 
  grd3 :  $Heart\_State = KO$ 
then
  act1 :  $Disease\_step8 := Nonspecific$ 
end

Event  $T\_Wave\_Assessment\_Inverted\_Yes\_PM \hat{=}$ 
  PM - pulmonary embolism this disease is already defined in previous development.

refines  $P\_Wave\_assessment\_Peaked\_Yes\_Check\_RAE$ 
when
  grd1 :  $P\_Wave\_Peak(II) \geq 3000$ 
  grd2 :  $P\_Wave\_Peak(V1) \geq 3000$ 
  grd3 :  $Disease\_step6 = RAE$ 
  grd4 :  $Heart\_State = KO$ 
  grd5 :  $(\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$ 
         $\vee$ 
         $Q\_Normal\_Status = FALSE))$ 
  A : step 8
then
  act1 :  $Disease\_step6 := pulmonary\_embolism$ 
end

END

```

An Event-B Specification of Step8_B_Ref
Generated Date: 25 Nov 2010 @ 03:39:38 PM

MACHINE Step8_B_Ref

REFINES Step8

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx, Step8_ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
Small_R_QS A small R or QS wave in V1 and V2
Slurred_S_duration Slurred S duration
Delta_Wave Delta Wave
Disease_step3
ST_elevation ST segment elevation (Coved or Saddle-back)
Epsilon_Wave Epsilon Wave or (a terminal notch in the QRS)
ST_seg_ele ST segment for elevation 1mm=0.1mV
Disease_step4
Q_Width Q wave width
Q_Depth Q wave depth
Q_Normal_Status Q wave normal or abnormal
Age_of_Inf Age of Infarct
Disease_step5
Mice_State
R_Depth R wave depth or height (also use in Step 7)
R_Normal_Status R wave normal or abnormal
Q_Wave_State Q wave states for all LEADS
P_Wave_Peak function to estimate the peak of LEADS signal
Disease_step6
Diphasic
PP_Interval
RR_Interval
P_Wave_Broad
S_Depth S wave depth or height

R_S_Ratio R wave and S wave Ratio function
T_Wave_State T wave patterns...
Disease_step8
T_Wave_State_B B for alternative method of T wave assessment
T_Normal_Status T wave normal or abnormal
Abnormal_Shaped_ST
Asy_T_Inversion_strain Asymmetric T wave Inversion strain pattern
T_inversion Deep T wave inversion
T_inversion_l_d T inversion Localized and Diffuse
Disease_step8_B
ST_depression

INVARIANTS

inv1 : $T_Wave_State_B \in LEADS \rightarrow T_State_B$
inv2 : $T_Normal_Status \in BOOL$
inv3 : $Abnormal_Shaped_ST \in LEADS \rightarrow BOOL$
inv4 : $Asy_T_Inversion_strain \in LEADS \rightarrow BOOL$
inv5 : $T_inversion \in LEADS \rightarrow \mathbb{N}$
inv6 : $T_inversion_l_d \in LEADS \rightarrow T_State_l_d$
inv7 : $Disease_step8_B \in Disease_states_Codes_step8B$
inv8 : $Sinus = Yes \wedge Disease_step8 = Definite_ischemia \Rightarrow Heart_State = KO$
inv9 : $Sinus = Yes \wedge Disease_step8 = Probable_ischemia \Rightarrow Heart_State = KO$
inv10 : $Sinus = Yes \wedge Disease_step8_B \in \{Cardiomyopathy, other_nonspecific\} \Rightarrow Heart_State = KO$

EVENTS

Initialisation

extended

begin

act1 : $RR_Int_equidistant \in LEADS \rightarrow BOOL$
act2 : $PP_Int_equidistant \in LEADS \rightarrow BOOL$
act3 : $P_Positive \in LEADS \rightarrow BOOL$
act4 : $Sinus := No$
act5 : $PP_Interval \in LEADS \rightarrow \mathbb{N}$
act6 : $RR_Interval \in LEADS \rightarrow \mathbb{N}$
act7 : $Heart_Rate \in 1..300$
act8 : $Heart_State := KO$
act9 : $PR_Int := 120$
act10 : $Disease_step2 := NDS2$
act11 : $QRS_Int := 50$
act12 : $Notched_R \in LEADS \rightarrow BOOL$
act13 : $Small_R_QS \in LEADS \rightarrow BOOL$
act14 : $Slurred_S_duration \in LEADS \rightarrow \mathbb{N}_1$
act15 : $M_Shape_Complex \in LEADS \rightarrow BOOL$
act16 : $Slurred_S \in LEADS \rightarrow BOOL$
act17 : $ST_elevation \in LEADS \rightarrow BOOL$
act18 : $Epsilon_Wave \in LEADS \rightarrow BOOL$

```

act19 : Delta_Wave := 0
act20 : Disease_step3 := NDS3
act21 : ST_seg_ele :∈ LEADS → ℕ
act22 : Disease_step4 := NDS4
act57 : ST_depression :∈ LEADS → ℕ
act23 : Q_Width :∈ LEADS → ℕ
act24 : Q_Depth :∈ LEADS → ℕ
act25 : Q_Normal_Status := FALSE
act26 : Mice_State := NMS
act27 : R_Depth :∈ LEADS → ℕ
act28 : R_Normal_Status := FALSE
act29 : Q_Wave_State :∈ LEADS → BOOL
act30 : Age_of_Inf :∈ Age_of_Infarct
act31 : Disease_step5 := NDS5
act32 : Diphasic :∈ LEADS → BOOL
act33 : P_Wave_Broad :∈ LEADS → ℕ
act34 : P_Wave_Peak :∈ LEADS → ℕ
act35 : Disease_step6 := NDS6
act36 : S_Depth :∈ LEADS → ℕ
act37 : R_S_Ratio :∈ LEADS → ℕ
act38 : T_Wave_State :∈ LEADS → T_State
act39 : Disease_step8 := NDS8
act40 : Abnormal_Shaped_ST :∈ LEADS → BOOL
act41 : Asy_T_Inversion_strain :∈ LEADS → BOOL
act43 : T_inversion_l_d :∈ LEADS → T_State_l_d
act42 : T_inversion :∈ LEADS → ℕ
act44 : Disease_step8_B := NDS8B
act45 : T_Wave_State_B :∈ LEADS → T_State_B
act46 : T_Normal_Status := FALSE

```

end

Event *Rhythm_test_TRUE* $\hat{=}$
Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

any

rate

where

```

grd1 : (∃ l. l ∈ {II, V1, V2} ∧ PP_Int.equidistant(l) = TRUE ∧
        RR_Int.equidistant(l) = TRUE ∧
        RR.Interval(l) = PP.Interval(l))
        ∧
        P.Positive(II) = TRUE

```

```

grd4 : rate ∈ 60 .. 100
      60..100 is the range of normal heart rate

```

```

grd5 : PR.Int ≤ 200
      Heart is Normal if PR ≤ 200 QRS.Int < 120
      HeartisNormalifQRS < 120

```

```

grd6 : Disease_step2 = NDS2
grd7 : Disease_step3 = NDS3
grd8 : Disease_step4 = NDS4

```

```

    grd10 : Disease_step5 = NDS5
    grd11 : Disease_step6 = NDS6
    grd12 : Disease_step8 = NDS8
    grd13 : Disease_step8_B = NDS8B
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := OK
  end

Event Rhythm_test_FALSE  $\hat{=}$ 
  Abnormal Rhythm with Rate

extends Rhythm_test_FALSE

  any
    rate
  where
    grd1 : ( $\forall l. l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \vee$ 
      RR_Int_equidistant(l) = FALSE  $\vee$ 
      RR_Interval(l)  $\neq$  PP_Interval(l))
       $\vee$ 
      P_Positive(II) = FALSE
    grd2 : rate  $\in$  1 .. 300
  then
    act1 : Sinus := No
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end

Event Rhythm_test_TRUE_Rate  $\hat{=}$ 
  Sinus Rhythm with abnormal Rate

extends Rhythm_test_TRUE_Rate

  any
    rate
  where
    grd1 : ( $\exists l. l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
      RR_Int_equidistant(l) = TRUE  $\wedge$ 
      RR_Interval(l) = PP_Interval(l))
       $\wedge$ 
      P_Positive(II) = TRUE
    grd5 : rate  $\in$  1 .. 300  $\setminus$  60 .. 100
      60..100 is the range of normal heart rate, so rest of no. is abnormal
    grd6 : Disease_step3 = WPW_Syndrome  $\vee$  Disease_step3 = Brugada_Syndrome  $\vee$ 
      Disease_step3 = RV_Dysplasia  $\vee$  Disease_step3 = IVCD
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end
end

```

```

Event PR_Test  $\hat{=}$ 
    PR Interval Test

extends PR_Test

    any
        pr
    where
        grd1 : pr  $\in$  120 .. 220
            time interval in (ms.)
        grd2 : pr > 200
        grd3 : Sinus = Yes
        grd4 : Heart_State = KO
    then
        act1 : PR_Int := pr
        act2 : Disease_step2 := First_degree_AV_Block
    end

Event QRS_Test_LBBB  $\hat{=}$ 
    QRS Complex Interval Test

extends QRS_Test_LBBB

    any
        qrs
    where
        grd1 : qrs  $\in$  50 .. 150
        grd2 : qrs  $\geq$  120
        grd3 : Sinus = Yes
        grd4 : Heart_State = KO
        grd5 : Notched_R(I) = TRUE  $\wedge$ 
            Notched_R(V5) = TRUE  $\wedge$ 
            Notched_R(V6) = TRUE
            Right Bundle Branch Block (RBBB)
        grd6 : Small_R_QS(V1) = TRUE  $\wedge$ 
            Small_R_QS(V2) = TRUE
        grd7 : Q_Wave_State(V1) = TRUE  $\wedge$ 
            Q_Wave_State(V2) = TRUE  $\wedge$ 
            Q_Wave_State(V3) = TRUE  $\wedge$ 
            Q_Wave_State(V4) = TRUE
            from step 5
        grd8 : R_Normal_Status = FALSE
            from step 5
    then
        act1 : QRS_Int := qrs
        act2 : Disease_step2 := LBBB
    end

Event QRS_Test_RBBB  $\hat{=}$ 
    Right Bundle Branch Block (RBBB)

extends QRS_Test_RBBB

    any

```

```

    qrs
  where
    grd1 : qrs ∈ 50 .. 150
    grd2 : qrs ≥ 120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : M_Shape_Complex(V1) = TRUE ∧
           M_Shape_Complex(V2) = TRUE
    grd7 : Slurred_S(I) = TRUE ∧
           Slurred_S(V5) = TRUE ∧
           Slurred_S(V6) = TRUE
    grd8 : Slurred_S_duration(I) > 40 ∧
           Slurred_S_duration(V5) > 40 ∧
           Slurred_S_duration(V6) > 40

  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := RBBB
  end

Event QRS_Test_Atypical_RLBBB_WPW_Syndrome ≐
  QRS Test for Atypical LBBB RBBB

extends QRS_Test_Atypical_RLBBB_WPW_Syndrome

  any
    sympt
    d_wave
    exmi
  where
    grd1 : QRS_Int ≥ 110
    grd2 : sympt = A_RBBB ∨ sympt = A_LBBB
    grd3 : d_wave ∈ ℕ
    grd4 : (d_wave + PR_Int) ≤ 120
           Delta_Wave + PR ≤ 120 Heart_State = KO
    grd5grd6 : Disease_step4 = Acute_inferior_MI
    grd7 : exmi ∈ Mice_State5 ∧ exmi = Exclude_Mimics_MI

  then
    act2 : Delta_Wave := d_wave
    act3 : Disease_step3 := WPW_Syndrome
  end

Event QRS_Test_Atypical_RBBB_Brugada_Syndrome ≐
  Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends QRS_Test_Atypical_RBBB_Brugada_Syndrome

  any
    sympt
    dis
  where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO

```

```

    grd3 : QRS_Int ≥ 110
    grd4 : Slurred_S(V5) = FALSE ∧
           Slurred_S(V6) = FALSE
    grd5 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, NDS3}
    grd6 : ST_elevation(V1) = TRUE ∧
           ST_elevation(V2) = TRUE
    grd7 : Sinus = Yes
  then
    act1 : Disease_step3 := Brugada_Syndrome
  end

Event QRS_Test_Atypical_RBBB_RV_Dysplasia ≐
  Right Ventricular Dysplasia

extends QRS_Test_Atypical_RBBB_RV_Dysplasia

  any
    sympt
    dis
  where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int ≥ 110
    grd4 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, NDS3}
    grd5 : Epsilon_Wave(V1) = TRUE ∧
           Epsilon_Wave(V3) = TRUE
  then
    act1 : Disease_step3 := RV_Dysplasia
  end

Event QRS_Test_Atypical_RBBB_IVCD ≐
  IVCD diagnosis

extends QRS_Test_Atypical_RBBB_IVCD

  any
    dis
  where
    grd1 : QRS_Int ≥ 110
    grd2 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, NDS3}
    grd3 : Heart_State = KO
  then
    act1 : Disease_step3 := IVCD
  end

Event ST_seg_elevation_YES ≐
  ST segment elevation...

extends ST_seg_elevation_YES

  when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes

```

```

    grd3 :          ∨
    ((∃l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
    (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
    ∧
    (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
    ∧ l1 ≠ k1
    ∧
    (
    (l1 = V1 ∧ k1 = V2) ∨
    (l1 = V2 ∧ k1 = V3) ∨
    (l1 = V3 ∧ k1 = V4) ∨
    (l1 = V4 ∧ k1 = V5) ∨
    (l1 = V5 ∧ k1 = V6)
    )
    ))
grd4 : Disease_step4 ∈ {Acute_inferior_MI, Acute_anterior_MI}
    then
        act1 : Disease_step4 := STEMI
    end

Event ST_seg_elevation_NOTCKMB_Yes ≐
Troponin or CK-MB positive YES

extends ST_seg_elevation_NOTCKMB_Yes

    when

        grd1 : Heart.State = KO
        grd2 : Sinus = Yes
        grd3 :          ∨
        (∀l1 · l1 ∈ {II, III, aVF} ⇒
        (ST_elevation(l1) = FALSE ∧ ST_seg_ele(l1) < 1000))
grd4 : ∃l, k · l ∈ LEADS ∧ k ∈ LEADS ∧
(ST_depression(l) ≥ 1000 ∧ ST_depression(k) ≥ 1000)
    ∧ l ≠ k
grd5 : Disease_step4 ∈ {Troponin, CK_MB}
    then
        act1 : Disease_step4 := Non_STEMI
    end

Event ST_seg_elevation_NO_TCKMB_No ≐
Troponin or CK-MB positive No

extends ST_seg_elevation_NO_TCKMB_No

    when

        grd1 : Heart.State = KO
        grd2 : Sinus = Yes
        grd3 :          ∨
        (∀l · l ∈ {II, III, aVF} ⇒
        (ST_elevation(l) = FALSE ∧ ST_seg_ele(l) < 1000))
grd4 : ∃l, k · l ∈ LEADS ∧ k ∈ LEADS ∧
(ST_depression(l) ≥ 1000 ∧ ST_depression(k) ≥ 1000)
    ∧ l ≠ k
grd5 : Disease_step4 ∉ {Troponin, CK_MB}
grd6 : ∀l · l ∈ LEADS ⇒ T_inversion(l) < 5000

```

```

grd7 : T_Normal_Status = FALSE
    then
        act1 : Disease_step4 := Ischemia
    end

Event Q_Assessment_Normal  $\hat{=}$ 
    Q wave assessment normal

extends Q_Assessment_Normal

when
    grd1 : Q_Width(II) < 40  $\wedge$  Q_Depth(II)  $\leq$  3000  $\wedge$ 
        Q_Width(aVF) < 40  $\wedge$  Q_Depth(aVF)  $\leq$  3000  $\wedge$ 
        Q_Width(aVL) < 40
        1000 micrometer = 1 millimeter
    grd2 : Q_Width(III)  $\leq$  40  $\wedge$  Q_Depth(III)  $\leq$  7000  $\wedge$  Q_Depth(aVL)  $\leq$  7000
    grd3 : Q_Depth(I) < 40  $\wedge$  Q_Depth(I)  $\leq$  1500
    then
        act1 : Q_Normal_Status := TRUE
    end

Event Q_Assessment_Abnormal_AMI  $\hat{=}$ 
    Q wave assessment abnormal for anterolateral MI (AMI)

extends Q_Assessment_Abnormal_AMI

when
    grd1 : Heart_State = K0
    grd2 : Sinus = Yes
    grd3 :  $\vee$ 
        (( $\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
        ( $ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE$ )
         $\wedge$ 
        ( $ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000$ )
         $\wedge l1 \neq k1$ 
         $\wedge$ 
        (
        ( $l1 = V1 \wedge k1 = V2$ )  $\vee$ 
        ( $l1 = V2 \wedge k1 = V3$ )  $\vee$ 
        ( $l1 = V3 \wedge k1 = V4$ )  $\vee$ 
        ( $l1 = V4 \wedge k1 = V5$ )  $\vee$ 
        ( $l1 = V5 \wedge k1 = V6$ )
        )
        ))
    grd4 : Q_Width(V5)  $\geq$  40  $\wedge$  Q_Depth(V5) > 3000  $\wedge$ 
        Q_Width(V6)  $\geq$  40  $\wedge$  Q_Depth(V6) > 3000
    grd5 : Q_Width(aVL)  $\geq$  40  $\wedge$  Q_Depth(aVL) > 7000
    grd6 : Q_Depth(I)  $\geq$  40  $\wedge$  Q_Depth(I) > 1500
    grd7 : Q_Normal_Status = FALSE
    then
        act1 : Disease_step4 := Acute_anterior_MI
    end

Event Q_Assessment_Abnormal_IMI  $\hat{=}$ 
    Q wave assessment abnormal for inferior MI (IMI)

```


extends *Q_Assessment_Abnormal_IMI*

when

grd1 : Heart_State = KO

grd2 : Sinus = Yes

grd3 : \vee

$((\exists l1, k1. l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
 $(ST_elevation(l1) = TRUE \wedge ST_elevation(k1) = TRUE)$

\wedge
 $(ST_seg_ele(l1) \geq 1000 \wedge ST_seg_ele(k1) \geq 1000)$
 $\wedge l1 \neq k1$

\wedge
(
 $(l1 = V1 \wedge k1 = V2) \vee$
 $(l1 = V2 \wedge k1 = V3) \vee$
 $(l1 = V3 \wedge k1 = V4) \vee$
 $(l1 = V4 \wedge k1 = V5) \vee$
 $(l1 = V5 \wedge k1 = V6)$
)

)
)

grd4 : $Q_Width(II) \geq 40 \wedge Q_Depth(II) > 3000 \wedge$
 $Q_Width(III) > 40 \wedge Q_Depth(III) > 7000 \wedge$
 $Q_Width(aVF) \geq 40 \wedge Q_Depth(aVF) > 3000$

grd5 : *Q_Normal_Status* = FALSE

then

act1 : *Disease_step4* := *Acute_inferior_MI*

end

Event *Determine_Age_of_Infarct* $\hat{=}$

extends *Determine_Age_of_Infarct*

when

grd1 : *Disease_step4* = *Acute_inferior_MI*

\vee

Disease_step5 \in {*anterior_MI*, *LVH*, *emphysema*}

\vee

Mice_State = *Exclude_Mimics_MI*

\vee

Disease_step2 = *LBBB*

then

act1 : *Age_of_Inf* \in {*recent*, *old*, *indeterminate*}

end

Event *Exclude_Mimics* $\hat{=}$

extends *Exclude_Mimics*

any

exmi

where

grd1 : *Disease_step4* = *Acute_inferior_MI*

grd2 : *exmi* \in *Mice_State5* \wedge *exmi* = *Exclude_Mimics_MI*

then

act1 : *Disease_step5* := *Hypertrophic_cardiomyopathy*

```

        act2 : Mice_State := borderline_Qs
    end

Event R_Assessment_Normal  $\hat{=}$ 
    Q wave assessment normal

extends R_Assessment_Normal

    any
        age
    where
        grd1 : R.Depth(V1)  $\geq$  0  $\wedge$  R.Depth(V1)  $\leq$  6000  $\wedge$  age > 30
            1000 micrometer= 1 millimeter
        grd2 : R.Depth(V2) > 200  $\wedge$  R.Depth(V2)  $\leq$  12000
        grd3 : R.Depth(V2)  $\geq$  1000  $\wedge$  R.Depth(V2)  $\leq$  24000
    then
        act1 : R.Normal_Status := TRUE
    end

Event R_Assessment_Abnormal  $\hat{=}$ 

extends R_Assessment_Abnormal

    when
        grd1 : R.Normal_Status = FALSE
    then
        act1 : Mice_State  $\in$  {late_transition, normal_variant}
    end

Event R_Q_Assessment_R_Abnormal_V1234  $\hat{=}$ 
    R wave abnormal , pathologic Q waves consider in V1-V4

extends R_Q_Assessment_R_Abnormal_V1234

    when
        grd1 : R.Normal_Status = FALSE
        grd2 : Q.Wave_State(V1) = TRUE  $\wedge$ 
            Q.Wave_State(V2) = TRUE  $\wedge$ 
            Q.Wave_State(V3) = TRUE  $\wedge$ 
            Q.Wave_State(V4) = TRUE
        grd3 : Heart_State = KO
    then
        act1 : Disease_step5  $\in$  {anterior_MI, LVH, emphysema}
        act2 : Mice_State := Exclude_Mimics_MI
    end

Event R_Q_Assessment_R_Abnormal_V56  $\hat{=}$ 
    R wave abnormal , pathologic Q waves consider in V5-V6

extends R_Q_Assessment_R_Abnormal_V56

    when
        grd1 : Q.Wave_State(V5) = TRUE  $\wedge$ 
            Q.Wave_State(V6) = TRUE
        grd3 : Heart_State = KO

```

```

    then
      act1 : Disease_step5 ∈ {lateral_MI, Hypertrophic_cardiomyopathy}
    end
  Event P_Wave_assessment_Peaked_Broad_No ≐
  extends P_Wave_assessment_Peaked_Broad_No
    when
      grd1 : (P_Wave_Peak(II) < 3000 ∧
              P_Wave_Peak(V1) < 3000)
              ∨
              (P_Wave_Broad(II) < 110 ∧ P_Wave_Broad(V1) < 110) ∨
              Diphasic(II) = FALSE ∨
              Diphasic(V1) = FALSE
    then
      act1 : Disease_step6 := NDS6
    end
  Event P_Wave_assessment_Peaked_Yes ≐
  extends P_Wave_assessment_Peaked_Yes
    when
      grd1 : P_Wave_Peak(II) ≥ 3000
      grd2 : P_Wave_Peak(V1) ≥ 3000
      grd3 : Heart_State = KO
    then
      act1 : Disease_step6 := RAE
    end
  Event P_Wave_assessment_Peaked_Yes_Check_RAE ≐
  extends P_Wave_assessment_Peaked_Yes_Check_RAE
    when
      grd1 : P_Wave_Peak(II) ≥ 3000
      grd2 : P_Wave_Peak(V1) ≥ 3000
      grd3 : Disease_step6 = RAE
      grd4 : Heart_State = KO
    then
      act1 : Disease_step6 := RV_strain
    end
  Event P_Wave_assessment_Broad_Yes ≐
  extends P_Wave_assessment_Broad_Yes
    when
      grd1 : (P_Wave_Broad(II) ≥ 110 ∧ P_Wave_Broad(V1) ≥ 110) ∨
              Diphasic(II) = TRUE ∨
              Diphasic(V1) = TRUE
      grd2 : Heart_State = KO
    then
      act1 : Disease_step6 := LAE
    end

```

```

end

Event P_Wave_assessment_Broad_Yes_Check_LAE ≐
extends P_Wave_assessment_Broad_Yes_Check_LAE

when
  grd1 : (P_Wave_Broad(II) ≥ 110 ∧ P_Wave_Broad(V1) ≥ 110) ∨
          Diphasic(II) = TRUE ∨
          Diphasic(V1) = TRUE
  grd2 : Disease_step6 = LAE
  grd3 : Heart_State = KO
then
  act1 : Disease_step6 ∈ {mitral_stenosis, mitral_regurgitation, LV_failure,
                          dilated_cardiomyopathy}
end

Event LVH_Assessment ≐
LVH_Assessment

refines LVH_Assessment

any
  LVH_specificity    specificity in percentage
  sensitivity         sensitivity in percentage
  sex
where
  grd1 : (P_Wave_Broad(II) ≥ 110 ∧ P_Wave_Broad(V1) ≥ 110) ∨
          Diphasic(II) = TRUE ∨
          Diphasic(V1) = TRUE
  grd2 : Disease_step6 = LAE
  grd5 : sex ∈ {0, 1}
          o for men and 1 for women
  grd3 : ((S_Depth(V1) + R_Depth(V5)) > 35000
          ∨
          (S_Depth(V1) + R_Depth(V6)) > 35000)
          1mm = 1000 micrometer..... 1 assessment
  grd4 : ((R_Depth(aVL) + S_Depth(V1) ≥ 24000) ∧ sex = 0)
          ∨
          ((R_Depth(aVL) + S_Depth(V1) ≥ 18000) ∧ sex = 1)
          2 assessment
  grd6 : LVH_specificity = 90
          ∧
          sensitivity < 40
          1 and 2 assessment
  grd7 : Disease_step6 = LAE ⇒ LVH_specificity < 98
          3 assessment
  grd8 : (∀t.t ∈ LEADS ⇒ ST_elevation(t) = TRUE
          ∨
          Q_Normal_Status = FALSE)
          A or B : from step 8 development
  grd9 : (∀l1, k1.l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
          ((ST_elevation(l1) = FALSE ∨ ST_elevation(k1) = FALSE)
          ∨

```

```

      ((ST_seg_ele(l1) < 1000 ∨ ST_seg_ele(k1) < 1000)
      ∧
      (Abnormal_Shaped_ST(l1) = FALSE ∨ Abnormal_Shaped_ST(k1) = FALSE)))
      ⇒ l1 ≠ k1))
grd10: Asy_T_Inversion_strain(V5) = TRUE ∧
      Asy_T_Inversion_strain(V6) = TRUE ∧
      Asy_T_Inversion_strain(V4) = TRUE
grd11: Heart_State = KO
grd12: T_Normal_Status = FALSE
  then
    act1: Disease_step6 := LVH_cause
  end

Event RVH_Assessment ≜
  RVH Assessment

refines RVH_Assessment

any
  age    age od men or women
  aixs   axis for deviation

where
  grd1: P_Wave_Peak(II) ≥ 3000
  grd2: P_Wave_Peak(V1) ≥ 3000
  grd3: Disease_step6 = RAE
  grd4: R_Depth(V1) ≥ 7000 ∧ age > 30
        1 assessment
  grd5: S_Depth(V5) ≥ 7000 ∨
        S_Depth(V6) ≥ 7000
        2 assessment
  grd6: R_S_Ratio(V1) ≥ 100
        R.S Ratio is multiply by 100 to remove the real no. constants... 3 assessment
  grd7: R_S_Ratio(V5) ≤ 100
        ∨
        R_S_Ratio(V6) ≤ 100
        4 assessment
  grd8: aixs ∈ 0 .. 360 ∧ aixs ≥ 110
        5 assessment
  grd9: Disease_step2 ∉ {LBBB, RBBB}
  grd10: QRS_Int < 120
  grd11: (∀t ∈ LEADS ⇒ ST_elevation(t) = TRUE
        ∨
        Q_Normal_Status = FALSE))

AorB: from_step8_development
  ∨
  (∀l1, k1 · l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
  ((ST_elevation(l1) = FALSE ∨ ST_elevation(k1) = FALSE)
  ∨
  ((ST_seg_ele(l1) < 1000 ∨ ST_seg_ele(k1) < 1000)
  ∧
  (Abnormal_Shaped_ST(l1) = FALSE ∨ Abnormal_Shaped_ST(k1) = FALSE)))
  ⇒ l1 ≠ k1))

```

```

grd13 : Asy_T_Inversion_strain(V1) = TRUE ∧
        Asy_T_Inversion_strain(V2) = TRUE ∧
        Asy_T_Inversion_strain(V3) = TRUE
grd14 : Heart_State = KO
grd15 : T_Normal_Status = FALSE
    then
        act1 : Disease_step6 := RVH
    end

Event T_Wave_Assessment_Peaked_V123456 ≐
    T Wave Assessment

extends T_Wave_Assessment_Peaked_V123456

when
    grd1 : Heart_State = KO
    grd2 : ∀l·l ∈ {V1, V2, V3, V4, V5, V6} ⇒ T_Wave_State(l) = Peaked
then
    act1 : Disease_step8 := Hyperkalemia
end

Event T_Wave_Assessment_Peaked_V12 ≐

refines T_Wave_Assessment_Peaked_V12

when
    grd1 : R_Normal_Status = FALSE
    grd2 : T_Wave_State(V1) = Peaked ∧
           T_Wave_State(V2) = Peaked
    grd3 :
        ∨
        ((∀l1, k1·l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
          ((ST_elevation(l1) = FALSE ∨ ST_elevation(k1) = FALSE)
          ∨
          ((ST_seg_ele(l1) < 1000 ∨ ST_seg_ele(k1) < 1000)
          ∧
          (Abnormal_Shaped_ST(l1) = FALSE ∨ Abnormal_Shaped_ST(k1) = FALSE)))
          ⇒ l1 ≠ k1))
grd4 : ∀l·l ∈ LEADS ⇒ T_inversion(l) < 5000
      step 8 B
grd5 : T_Normal_Status = FALSE
    then
        act1 : Mice_State := normal_variant
    end

Event T_Wave_Assessment_Peaked_V12_MI ≐
    posterior MI using T wave assessment in LEADS V1 and V2

refines T_Wave_Assessment_Peaked_V12_MI

when
    grd1 : T_Wave_State(V1) = Peaked ∧
           T_Wave_State(V2) = Peaked
    grd6 : Heart_State = KO

```

```

    grd2 :  $\vee$ 
      ( $\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
      ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
       $\vee$ 
      ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
       $\wedge$ 
      ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ ))
       $\Rightarrow l1 \neq k1$ )
grd3 :  $\forall l. l \in LEADS \Rightarrow T\_inversion(l) > 5000$ 
grd4 :  $T\_inversion\_L\_d(V2) = Localized \wedge$ 
       $T\_inversion\_L\_d(V3) = Localized \wedge$ 
       $T\_inversion\_L\_d(V4) = Localized \wedge$ 
       $T\_inversion\_L\_d(V5) = Localized$ 
grd5 :  $T\_inversion\_L\_d(II) = Localized \wedge$ 
       $T\_inversion\_L\_d(III) = Localized \wedge$ 
       $T\_inversion\_L\_d(aVF) = Localized$ 
grd7 :  $T\_Normal\_Status = FALSE$ 
  then
    act1 :  $Disease\_step8 := posterior\_MI$ 
  end
Event  $T\_Wave\_Assessment\_Flat \hat{=}$ 
refines  $T\_Wave\_Assessment\_Flat$ 
  when
    grd1 :  $\forall l. l \in LEADS \Rightarrow T\_Wave\_State(l) = Flat$ 
    grd4 :  $Heart\_State = KO$ 
    grd2 :  $\vee$ 
      ( $\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
      ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
       $\vee$ 
      ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
       $\wedge$ 
      ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ ))
       $\Rightarrow l1 \neq k1$ )
  step 8 B
grd3 :  $\forall l. l \in LEADS \Rightarrow T\_inversion(l) < 5000$ 
grd5 :  $T\_Normal\_Status = FALSE$ 
  then
    act1 :  $Disease\_step8 := Nonspecific\_ST\_T\_changes$ 
    act2 :  $Disease\_step8\_B := \{Cardiomyopathy, Electrolyte\_depletion, Alcohol, Myocarditis, Other\}$ 
  end
Event  $T\_Wave\_Assessment\_Inverted\_Yes \hat{=}$ 
extends  $T\_Wave\_Assessment\_Inverted\_Yes$ 
  when
    grd1 :  $\forall l. l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$ 
    grd2 :  $\forall l. l \in LEADS \Rightarrow ST\_elevation(l) = TRUE$ 
       $\vee$ 
       $Q\_Normal\_Status = FALSE$ 
    grd3 :  $Heart\_State = KO$ 
  then

```

```

    act1 : Disease_step8 := {Definite_ischemia, Probable_ischemia, Digitalis_effect}
  end
Event T_Wave_Assessment_Inverted_No  $\hat{=}$ 
extends T_Wave_Assessment_Inverted_No
  when
    grd1 :  $\forall l \cdot l \in \text{LEADS} \Rightarrow \text{T\_Wave\_State}(l) = \text{Inverted}$ 
    grd2 :  $\forall l \cdot l \in \text{LEADS} \Rightarrow \text{ST\_elevation}(l) = \text{FALSE}$ 
            $\vee$ 
           Q_Normal_Status = TRUE
    grd3 : Heart_State = KO
  then
    act1 : Disease_step8 := Nonspecific
  end
Event T_Wave_Assessment_Inverted_Yes_PM  $\hat{=}$ 
  PM - pulmonary embolism this disease is already defined in previous development.
refines T_Wave_Assessment_Inverted_Yes_PM
  when
    grd1 : P_Wave_Peak(II)  $\geq$  3000
    grd2 : P_Wave_Peak(V1)  $\geq$  3000
    grd3 : Disease_step6 = RAE
    grd4 :  $(\forall t \cdot t \in \text{LEADS} \Rightarrow \text{ST\_elevation}(t) = \text{TRUE})$ 
            $\vee$ 
           (Q_Normal_Status = FALSE))
  then
    act1 : Disease_step8 := pulmonary_embolism
  end
Event T_Wave_Assessment_B  $\hat{=}$ 
  B for alternate method of T wave assessment
  when
    grd1 :  $\forall l \cdot l \in \{I, II, V3, V4, V5, V6\} \Rightarrow \text{T\_Wave\_State\_B}(l) = \text{Upright}$ 
    grd2 :  $\text{T\_Wave\_State\_B}(aVL) = \text{Inverted\_B}$ 
    grd3 :  $\forall l \cdot l \in \{III, aVF, V1, V2\} \Rightarrow \text{T\_Wave\_State\_B}(l) = \text{Variable}$ 
  then

```



```

    act1 : T_Normal_Status := TRUE
end

Event T_Wave_Assessment_B_DI ≐
  abnormal T wave .....in B ...DI(Definite Ischemia)

refines T_Wave_Assessment_Inverted_Yes

when
  grd1 :  $\forall l \cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$ 
  grd2 :  $\forall l \cdot l \in LEADS \Rightarrow ST\_elevation(l) = TRUE$ 
     $\vee$ 
    Q_Normal_Status = FALSE
  grd3 : T_Normal_Status = FALSE
    added in step-8 B
  grd5 : Heart_State = KO
  grd4 :  $\exists l, k \cdot l \in LEADS \wedge k \in LEADS \wedge$ 
     $((ST\_seg\_ele(l) \geq 1000 \wedge ST\_seg\_ele(k) \geq 1000) \vee$ 
     $(ST\_elevation(l) = TRUE \wedge ST\_elevation(k) = TRUE))$ 
     $\vee$ 
     $(Abnormal\_Shaped\_ST(l) = TRUE \wedge Abnormal\_Shaped\_ST(k) = TRUE))$ 
     $\wedge$ 
     $l \neq k$ 
    added in step-8 B

then
  act1 : Disease_step8 := Definite_ischemia
end

Event T_Inversion_Likely_Ischemia ≐
  probable Ischemia or Likly ischemia

refines T_Wave_Assessment_Inverted_Yes

when
  grd1 :  $\forall l \cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$ 
  grd2 :  $\forall l \cdot l \in LEADS \Rightarrow ST\_elevation(l) = TRUE$ 
     $\vee$ 
    Q_Normal_Status = FALSE
  grd3 :  $\forall l \cdot l \in LEADS \Rightarrow T\_inversion(l) > 5000$ 
    1 mm= 1000
  grd4 :  $\vee$ 
     $(\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
     $((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$ 
     $\vee$ 
     $((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$ 
     $\wedge$ 
     $(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$ 
     $\Rightarrow l1 \neq k1))$ 
  grd5 : T_inversion_L_d(V2) = Localized  $\wedge$ 
    T_inversion_L_d(V3) = Localized  $\wedge$ 
    T_inversion_L_d(V4) = Localized  $\wedge$ 
    T_inversion_L_d(V5) = Localized
  grd6 : T_inversion_L_d(II) = Localized  $\wedge$ 
    T_inversion_L_d(III) = Localized  $\wedge$ 
    T_inversion_L_d(aVF) = Localized
  b. of Deep inversion  $i$  5mm

```

```

grd7 : Heart_State = KO
grd8 : T_Normal_Status = FALSE
    then
        act1 : Disease_step8 := Probable_ischemia
    end
Event T_Inversion_Diffuse_B  $\hat{=}$ 
    Step 8 B for c.
    when
        grd1 :  $\vee$ 
            (( $\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
            ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
             $\vee$ 
            ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
             $\wedge$ 
            ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ )))
             $\Rightarrow l1 \neq k1$ )
grd2 :  $\forall l. l \in LEADS \Rightarrow T\_inversion(l) > 5000$ 
grd3 :  $\forall l. l \in LEADS \Rightarrow T\_inversion\_l\_d(l) = Diffuse$ 
grd4 : Heart_State = KO
grd5 : T_Normal_Status = FALSE
    then
        act1 : Disease_step8_B := {Cardiomyopathy, other_nonspecific}
    end
END

```

CONTEXT Step9

SETS

QRS_directions
Axis_deviation
Disease_Codes_Step9

CONSTANTS

D_Upright
D_Positive
D_Negative
LAD
RAD
ND
LAFB LAFB (hemiblock)
MSCHD Mechanical shifts causing a horizontal heart; high diaphragm; pregnancy, ascites
Some_Form_VT
ED_OC Endocardial cushion defects and other congenital heart disease
LPFB
Dextrocardia
NV_MSEC Normal variants: mechanical shifts or emphysema causing a vertical heart
NDS9

AXIOMS

axm1 : $QRS_directions = \{D_Upright, D_Positive, D_Negative\}$
axm2 : $\neg D_Upright = D_Positive$
axm3 : $\neg D_Upright = D_Negative$
axm4 : $\neg D_Positive = D_Negative$
axm5 : $Axis_deviation = \{LAD, RAD, ND\}$
axm6 : $\neg LAD = RAD$
axm7 : $\neg LAD = ND$
axm8 : $\neg RAD = ND$
axm9 : $Disease_Codes_Step9 = \{LAFB, MSCHD, Some_Form_VT, ED_OC, LPFB, Dextrocardia, NV_MSEC, NDS9\}$
axm10 : $\neg LAFB = MSCHD$
axm11 : $\neg LAFB = Some_Form_VT$
axm12 : $\neg LAFB = ED_OC$
axm13 : $\neg LAFB = LPFB$
axm14 : $\neg LAFB = Dextrocardia$
axm15 : $\neg LAFB = NV_MSEC$
axm16 : $\neg LAFB = NDS9$
axm17 : $\neg MSCHD = Some_Form_VT$
axm18 : $\neg MSCHD = ED_OC$

axm19 : $\neg MSCHD = LPFB$
axm20 : $\neg MSCHD = Dextrocardia$
axm21 : $\neg MSCHD = NV_MSEC$
axm22 : $\neg MSCHD = NDS9$
axm23 : $\neg Some_Form_VT = ED_OC$
axm24 : $\neg Some_Form_VT = LPFB$
axm25 : $\neg Some_Form_VT = Dextrocardia$
axm26 : $\neg Some_Form_VT = NV_MSEC$
axm27 : $\neg Some_Form_VT = NDS9$
axm28 : $\neg ED_OC = LPFB$
axm29 : $\neg ED_OC = Dextrocardia$
axm30 : $\neg ED_OC = NV_MSEC$
axm31 : $\neg ED_OC = NDS9$
axm32 : $\neg LPFB = Dextrocardia$
axm33 : $\neg LPFB = NV_MSEC$
axm34 : $\neg LPFB = NDS9$
axm35 : $\neg Dextrocardia = NV_MSEC$
axm36 : $\neg Dextrocardia = NDS9$
axm37 : $\neg NV_MSEC = NDS9$

END

An Event-B Specification of Step9_Axis_Assessment
Generated Date: 25 Nov 2010 @ 03:39:41 PM

MACHINE Step9_Axis_Assessment

REFINES Step8_B_Ref

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx, Step8_ctx, Step9

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
Small_R_QS A small R or QS wave in V1 and V2
Slurred_S_duration Slurred S duration
Delta_Wave Delta Wave
Disease_step3
ST_elevation ST segment elevation (Coved or Saddle-back)
Epsilon_Wave Epsilon Wave or (a terminal notch in the QRS)
ST_seg_ele ST segment for elevation 1mm=0.1mV
Disease_step4
Q_Width Q wave width
Q_Depth Q wave depth
Q_Normal_Status Q wave normal or abnormal
Age_of_Inf Age of Infarct
Disease_step5
Mice_State
R_Depth R wave depth or height (also use in Step 7)
R_Normal_Status R wave normal or abnormal
PP_Interval
RR_Interval
Q_Wave_State Q wave states for all LEADS
P_Wave_Peak function to estimate the peak of LEADS signal
Disease_step6
Diphasic
P_Wave_Broad
S_Depth S wave depth or height

R_S_Ratio R wave and S wave Ratio function
T_Wave_State T wave patterns...
Disease_step8
T_Wave_State_B B for alternative method of T wave assessment
T_Normal_Status T wave normal or abnormal
Abnormal_Shaped_ST
Asy_T_Inversion_strain Asymmetric T wave Inversion strain pattern
T_inversion Deep T wave inversion
T_inversion_l_d T inversion Localized and Diffuse
Disease_step8_B
QRS_Axis_State QRS Axis Direction
minAngle min. value of angle of Axis in degree
maxAngle max. value of angle of Axis in degree
ST_depression

INVARIANTS

inv1: $QRS_Axis_State \in LEADS \rightarrow QRS_directions$
inv2: $minAngle \in -90 .. 180$
inv3: $maxAngle \in -90 .. 180$

EVENTS

Initialisation

extended

begin

act1: $RR_Int_equidistant : \in LEADS \rightarrow BOOL$
act2: $PP_Int_equidistant : \in LEADS \rightarrow BOOL$
act3: $P_Positive : \in LEADS \rightarrow BOOL$
act4: $Sinus := No$
act5: $PP_Interval : \in LEADS \rightarrow \mathbb{N}$
act6: $RR_Interval : \in LEADS \rightarrow \mathbb{N}$
act7: $Heart_Rate : \in 1 .. 300$
act8: $Heart_State := KO$
act9: $PR_Int := 120$
act10: $Disease_step2 := NDS2$
act11: $QRS_Int := 50$
act12: $Notched_R : \in LEADS \rightarrow BOOL$
act13: $Small_R_QS : \in LEADS \rightarrow BOOL$
act14: $Slurred_S_duration : \in LEADS \rightarrow \mathbb{N}_1$
act15: $M_Shape_Complex : \in LEADS \rightarrow BOOL$
act16: $Slurred_S : \in LEADS \rightarrow BOOL$
act17: $ST_elevation : \in LEADS \rightarrow BOOL$
act18: $Epsilon_Wave : \in LEADS \rightarrow BOOL$
act19: $Delta_Wave := 0$
act20: $Disease_step3 := NDS3$
act21: $ST_seg_ele : \in LEADS \rightarrow \mathbb{N}$
act22: $Disease_step4 := NDS4$
act57: $ST_depression : \in LEADS \rightarrow \mathbb{N}$

```

act23 : Q_Width :∈ LEADS → ℕ
act24 : Q_Depth :∈ LEADS → ℕ
act25 : Q_Normal_Status := FALSE
act26 : Mice_State := NMS
act27 : R_Depth :∈ LEADS → ℕ
act28 : R_Normal_Status := FALSE
act29 : Q_Wave_State :∈ LEADS → BOOL
act30 : Age_of_Inf :∈ Age_of_Infarct
act31 : Disease_step5 := NDS5
act32 : Diphasic :∈ LEADS → BOOL
act33 : P_Wave_Broad :∈ LEADS → ℕ
act34 : P_Wave_Peak :∈ LEADS → ℕ
act35 : Disease_step6 := NDS6
act36 : S_Depth :∈ LEADS → ℕ
act37 : R_S_Ratio :∈ LEADS → ℕ
act38 : T_Wave_State :∈ LEADS → T_State
act39 : Disease_step8 := NDS8
act40 : Abnormal_Shaped_ST :∈ LEADS → BOOL
act41 : Asy_T_Inversion_strain :∈ LEADS → BOOL
act43 : T_inversion_l_d :∈ LEADS → T_State_l_d
act42 : T_inversion :∈ LEADS → ℕ
act44 : Disease_step8_B := NDS8B
act45 : T_Wave_State_B :∈ LEADS → T_State_B
act46 : T_Normal_Status := FALSE
act47 : QRS_Axis_State :∈ LEADS → QRS_directions
act48 : minAngle := 0
act49 : maxAngle := 0

```

end

Event *Rhythm_test.TRUE* $\hat{=}$
Sinus Rhythm with Normal Rate

extends *Rhythm_test.TRUE*

any

rate

where

```

grd1 : (∃ l.1 ∈ {II, V1, V2} ∧ PP_Int.equidistant(l) = TRUE ∧
      RR_Int.equidistant(l) = TRUE ∧
      RR_Interval(l) = PP_Interval(l))
      ∧
      P_Positive(II) = TRUE

```

grd4 : rate ∈ 60 .. 100
60..100 is the range of normal heart rate

grd5 : PR_Int ≤ 200
Heart is Normal if PR ≤ 200 QRS_Int < 120
HeartisNormalifQRS < 120

grd7 : Disease_step2 = NDS2

grd8 : Disease_step3 = NDS3

grd9 : Disease_step4 = NDS4

grd10 : Disease_step5 = NDS5

grd11 : Disease_step6 = NDS6

```

    grd12 : Disease_step8 = NDS8
    grd13 : Disease_step8_B = NDS8B
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := OK
  end
Event Rhythm_test.FALSE  $\hat{=}$ 
  Abnormal Rhythm with Rate
extends Rhythm_test.FALSE
  any
    rate
  where
    grd1 : ( $\forall l. l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \vee$ 
      RR_Int_equidistant(l) = FALSE  $\vee$ 
      RR_Interval(l)  $\neq$  PP_Interval(l))
       $\vee$ 
      P_Positive(II) = FALSE
    grd2 : rate  $\in$  1 .. 300
  then
    act1 : Sinus := No
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end
Event Rhythm_test.TRUE_Rate  $\hat{=}$ 
  Sinus Rhythm with abnormal Rate
extends Rhythm_test.TRUE_Rate
  any
    rate
  where
    grd1 : ( $\exists l. l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
      RR_Int_equidistant(l) = TRUE  $\wedge$ 
      RR_Interval(l) = PP_Interval(l))
       $\wedge$ 
      P_Positive(II) = TRUE
    grd5 : rate  $\in$  1 .. 300  $\setminus$  60 .. 100
      60..100 is the range of normal heart rate, so rest of no. is abnormal
    grd6 : Disease_step3 = WPW_Syndrome  $\vee$  Disease_step3 = Brugada_Syndrome  $\vee$ 
      Disease_step3 = RV_Dysplasia  $\vee$  Disease_step3 = IVCD
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end
Event PR_Test  $\hat{=}$ 
  PR Interval Test

```



```

extends PR_Test
  any
    pr
  where
    grd1 : pr ∈ 120 .. 220
           time interval in (ms.)
    grd2 : pr > 200
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
  then
    act1 : PR_Int := pr
    act2 : Disease_step2 := First_degree_AV_Block
  end

```

```

Event QRS_Test_LBBB ≐
  QRS Complex Interval Test

```

```

extends QRS_Test_LBBB
  any
    qrs
  where
    grd1 : qrs ∈ 50 .. 150
    grd2 : qrs ≥ 120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : Notched_R(I) = TRUE ∧
           Notched_R(V5) = TRUE ∧
           Notched_R(V6) = TRUE
           Right Bundle Branch Block (RBBB)
    grd6 : Small_R_QS(V1) = TRUE ∧
           Small_R_QS(V2) = TRUE
    grd7 : Q_Wave_State(V1) = TRUE ∧
           Q_Wave_State(V2) = TRUE ∧
           Q_Wave_State(V3) = TRUE ∧
           Q_Wave_State(V4) = TRUE
           from step 5
    grd8 : R_Normal_Status = FALSE
           from step 5
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := LBBB
  end

```

```

Event QRS_Test_RBBB ≐
  Right Bundle Branch Block (RBBB)

```

```

extends QRS_Test_RBBB
  any
    qrs
  where

```

```

    grd1 : qrs ∈ 50 .. 150
    grd2 : qrs ≥ 120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : M_Shape_Complex(V1) = TRUE ∧
           M_Shape_Complex(V2) = TRUE
    grd7 : Slurred_S(I) = TRUE ∧
           Slurred_S(V5) = TRUE ∧
           Slurred_S(V6) = TRUE
    grd8 : Slurred_S_duration(I) > 40 ∧
           Slurred_S_duration(V5) > 40 ∧
           Slurred_S_duration(V6) > 40
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := RBBB
  end
Event QRS_Test_Atypical_RLBBB_WPW_Syndrome ≐
  QRS Test for Atypical LBBB RBBB
extends QRS_Test_Atypical_RLBBB_WPW_Syndrome
  any
    sympt
    d_wave
    exmi
  where
    grd1 : QRS_Int ≥ 110
    grd2 : sympt = A_RBBB ∨ sympt = A_LBBB
    grd3 : d_wave ∈ ℕ
    grd4 : (d_wave + PR_Int) ≤ 120
           Delta_Wave + PR ≤ 120 Heart_State = KO
    grd5 grd6 : Disease_step4 = Acute_inferior_MI
    grd7 : exmi ∈ Mice_State5 ∧ exmi = Exclude_Mimics_MI
  then
    act2 : Delta_Wave := d_wave
    act3 : Disease_step3 := WPW_Syndrome
  end
Event QRS_Test_Atypical_RBBB_Brugada_Syndrome ≐
  Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6
extends QRS_Test_Atypical_RBBB_Brugada_Syndrome
  any
    sympt
    dis
  where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int ≥ 110
    grd4 : Slurred_S(V5) = FALSE ∧
           Slurred_S(V6) = FALSE

```

```

    grd5 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, NDS3}
    grd6 : ST_elevation(V1) = TRUE ∧
           ST_elevation(V2) = TRUE
    grd7 : Sinus = Yes
  then
    act1 : Disease_step3 := Brugada_Syndrome
  end
Event QRS_Test_Atypical_RBBB_RV_Dysplasia ≐
  Right Ventricular Dysplasia
extends QRS_Test_Atypical_RBBB_RV_Dysplasia
  any
    sympt
    dis
  where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int ≥ 110
    grd4 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, NDS3}
    grd5 : Epsilon_Wave(V1) = TRUE ∧
           Epsilon_Wave(V3) = TRUE
  then
    act1 : Disease_step3 := RV_Dysplasia
  end
Event QRS_Test_Atypical_RBBB_IVCD ≐
  IVCD diagnosis
extends QRS_Test_Atypical_RBBB_IVCD
  any
    dis
  where
    grd1 : QRS_Int ≥ 110
    grd2 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, NDS3}
    grd3 : Heart_State = KO
  then
    act1 : Disease_step3 := IVCD
  end
Event ST_seg_elevation_YES ≐
  ST segment elevation...
extends ST_seg_elevation_YES
  when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes

```

```

    grd3 :          ∨
    ((∃l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
    (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
    ∧
    (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
    ∧ l1 ≠ k1
    ∧
    (
    (l1 = V1 ∧ k1 = V2) ∨
    (l1 = V2 ∧ k1 = V3) ∨
    (l1 = V3 ∧ k1 = V4) ∨
    (l1 = V4 ∧ k1 = V5) ∨
    (l1 = V5 ∧ k1 = V6)
    )
    ))
grd4 : Disease_step4 ∈ {Acute_inferior_MI, Acute_anterior_MI}
    then
        act1 : Disease_step4 := STEMI
    end

Event ST_seg_elevation_NOTCKMB_Yes ≐
Troponin or CK-MB positive YES

extends ST_seg_elevation_NOTCKMB_Yes

    when

        grd1 : Heart.State = KO
        grd2 : Sinus = Yes
        grd3 :          ∨
        (∀l1 · l1 ∈ {II, III, aVF} ⇒
        (ST_elevation(l1) = FALSE ∧ ST_seg_ele(l1) < 1000))
grd4 : ∃l, k · l ∈ LEADS ∧ k ∈ LEADS ∧
(ST_depression(l) ≥ 1000 ∧ ST_depression(k) ≥ 1000)
    ∧ l ≠ k
grd5 : Disease_step4 ∈ {Troponin, CK_MB}
    then
        act1 : Disease_step4 := Non_STEMI
    end

Event ST_seg_elevation_NO_TCKMB_No ≐
Troponin or CK-MB positive No

extends ST_seg_elevation_NO_TCKMB_No

    when

        grd1 : Heart.State = KO
        grd2 : Sinus = Yes
        grd3 :          ∨
        (∀l · l ∈ {II, III, aVF} ⇒
        (ST_elevation(l) = FALSE ∧ ST_seg_ele(l1) < 1000))
grd4 : ∃l, k · l ∈ LEADS ∧ k ∈ LEADS ∧
(ST_depression(l) ≥ 1000 ∧ ST_depression(k) ≥ 1000)
    ∧ l ≠ k
grd5 : Disease_step4 ∉ {Troponin, CK_MB}
grd6 : ∀l · l ∈ LEADS ⇒ T_inversion(l) < 5000

```

```

grd7 : T_Normal_Status = FALSE
    then
        act1 : Disease_step4 := Ischemia
    end

Event Q_Assessment_Normal  $\hat{=}$ 
    Q wave assessment normal

extends Q_Assessment_Normal

when
    grd1 : Q_Width(II) < 40  $\wedge$  Q_Depth(II)  $\leq$  3000  $\wedge$ 
        Q_Width(aVF) < 40  $\wedge$  Q_Depth(aVF)  $\leq$  3000  $\wedge$ 
        Q_Width(aVL) < 40
        1000 micrometer = 1 millimeter
    grd2 : Q_Width(III)  $\leq$  40  $\wedge$  Q_Depth(III)  $\leq$  7000  $\wedge$  Q_Depth(aVL)  $\leq$  7000
    grd3 : Q_Depth(I) < 40  $\wedge$  Q_Depth(I)  $\leq$  1500

    then
        act1 : Q_Normal_Status := TRUE
    end

Event Q_Assessment_Abnormal_AMI  $\hat{=}$ 
    Q wave assessment abnormal for anterolateral MI (AMI)

extends Q_Assessment_Abnormal_AMI

when
    grd1 : Heart_State = K0
    grd2 : Sinus = Yes
    grd3 :  $\vee$ 
        (( $\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
        ( $ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE$ )
         $\wedge$ 
        ( $ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000$ )
         $\wedge l1 \neq k1$ 
         $\wedge$ 
        (
        ( $l1 = V1 \wedge k1 = V2$ )  $\vee$ 
        ( $l1 = V2 \wedge k1 = V3$ )  $\vee$ 
        ( $l1 = V3 \wedge k1 = V4$ )  $\vee$ 
        ( $l1 = V4 \wedge k1 = V5$ )  $\vee$ 
        ( $l1 = V5 \wedge k1 = V6$ )
        )
        ))

grd4 : Q_Width(V5)  $\geq$  40  $\wedge$  Q_Depth(V5) > 3000  $\wedge$ 
    Q_Width(V6)  $\geq$  40  $\wedge$  Q_Depth(V6) > 3000
grd5 : Q_Width(aVL)  $\geq$  40  $\wedge$  Q_Depth(aVL) > 7000
grd6 : Q_Depth(I)  $\geq$  40  $\wedge$  Q_Depth(I) > 1500
grd7 : Q_Normal_Status = FALSE

    then
        act1 : Disease_step4 := Acute_anterior_MI
    end

Event Q_Assessment_Abnormal_IMI  $\hat{=}$ 
    Q wave assessment abnormal for inferior MI (IMI)

```

extends *Q_Assessment_Abnormal_IMI*

when

grd1 : Heart_State = KO

grd2 : Sinus = Yes

grd3 : \vee

$((\exists l1, k1. l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$
 $(ST_elevation(l1) = TRUE \wedge ST_elevation(k1) = TRUE)$

\wedge
 $(ST_seg_ele(l1) \geq 1000 \wedge ST_seg_ele(k1) \geq 1000)$
 $\wedge l1 \neq k1$

\wedge
(
 $(l1 = V1 \wedge k1 = V2) \vee$
 $(l1 = V2 \wedge k1 = V3) \vee$
 $(l1 = V3 \wedge k1 = V4) \vee$
 $(l1 = V4 \wedge k1 = V5) \vee$
 $(l1 = V5 \wedge k1 = V6)$
)
)

grd4 : $Q_Width(II) \geq 40 \wedge Q_Depth(II) > 3000 \wedge$
 $Q_Width(III) > 40 \wedge Q_Depth(III) > 7000 \wedge$
 $Q_Width(aVF) \geq 40 \wedge Q_Depth(aVF) > 3000$

grd5 : *Q_Normal_Status* = FALSE

then

act1 : *Disease_step4* := *Acute_inferior_MI*

end

Event *Determine_Age_of_Infarct* $\hat{=}$

extends *Determine_Age_of_Infarct*

when

grd1 : *Disease_step4* = *Acute_inferior_MI*

\vee

Disease_step5 \in {*anterior_MI*, *LVH*, *emphysema*}

\vee

Mice_State = *Exclude_Mimics_MI*

\vee

Disease_step2 = *LBBB*

then

act1 : *Age_of_Inf* \in {*recent*, *old*, *indeterminate*}

end

Event *Exclude_Mimics* $\hat{=}$

extends *Exclude_Mimics*

any

exmi

where

grd1 : *Disease_step4* = *Acute_inferior_MI*

grd2 : *exmi* \in *Mice_State5* \wedge *exmi* = *Exclude_Mimics_MI*

then

act1 : *Disease_step5* := *Hypertrophic_cardiomyopathy*

```

        act2 : Mice_State := borderline_Qs
    end
Event R_Assessment_Normal  $\hat{=}$ 
    Q wave assessment normal
extends R_Assessment_Normal
    any
        age
    where
        grd1 : R.Depth(V1)  $\geq$  0  $\wedge$  R.Depth(V1)  $\leq$  6000  $\wedge$  age > 30
            1000 micrometer= 1 millimeter
        grd2 : R.Depth(V2) > 200  $\wedge$  R.Depth(V2)  $\leq$  12000
        grd3 : R.Depth(V2)  $\geq$  1000  $\wedge$  R.Depth(V2)  $\leq$  24000
    then
        act1 : R.Normal_Status := TRUE
    end
Event R_Assessment_Abnormal  $\hat{=}$ 
extends R_Assessment_Abnormal
    when
        grd1 : R.Normal_Status = FALSE
    then
        act1 : Mice_State  $\in$  {late_transition, normal_variant}
    end
Event R_Q_Assessment_R_Abnormal_V1234  $\hat{=}$ 
    R wave abnormal , pathologic Q waves consider in V1-V4
extends R_Q_Assessment_R_Abnormal_V1234
    when
        grd1 : R.Normal_Status = FALSE
        grd2 : Q.Wave_State(V1) = TRUE  $\wedge$ 
            Q.Wave_State(V2) = TRUE  $\wedge$ 
            Q.Wave_State(V3) = TRUE  $\wedge$ 
            Q.Wave_State(V4) = TRUE
        grd3 : Heart_State = KO
    then
        act1 : Disease_step5  $\in$  {anterior_MI, LVH, emphysema}
        act2 : Mice_State := Exclude_Mimics_MI
    end
Event R_Q_Assessment_R_Abnormal_V56  $\hat{=}$ 
    R wave abnormal , pathologic Q waves consider in V5-V6
extends R_Q_Assessment_R_Abnormal_V56
    when
        grd1 : Q.Wave_State(V5) = TRUE  $\wedge$ 
            Q.Wave_State(V6) = TRUE
        grd3 : Heart_State = KO

```

```

    then
      act1 : Disease_step5 ∈ {lateral_MI, Hypertrophic_cardiomyopathy}
    end
Event P_Wave_assessment_Peaked_Broad_No ≐
extends P_Wave_assessment_Peaked_Broad_No
  when
    grd1 : (P_Wave_Peak(II) < 3000 ∧
            P_Wave_Peak(V1) < 3000)
            ∨
            (P_Wave_Broad(II) < 110 ∧ P_Wave_Broad(V1) < 110) ∨
            Diphasic(II) = FALSE ∨
            Diphasic(V1) = FALSE
  then
    act1 : Disease_step6 := NDS6
  end
Event P_Wave_assessment_Peaked_Yes ≐
extends P_Wave_assessment_Peaked_Yes
  when
    grd1 : P_Wave_Peak(II) ≥ 3000
    grd2 : P_Wave_Peak(V1) ≥ 3000
    grd3 : Heart_State = KO
  then
    act1 : Disease_step6 := RAE
  end
Event P_Wave_assessment_Peaked_Yes_Check_RAE ≐
extends P_Wave_assessment_Peaked_Yes_Check_RAE
  when
    grd1 : P_Wave_Peak(II) ≥ 3000
    grd2 : P_Wave_Peak(V1) ≥ 3000
    grd3 : Disease_step6 = RAE
    grd4 : Heart_State = KO
  then
    act1 : Disease_step6 := RV_strain
  end
Event P_Wave_assessment_Broad_Yes ≐
extends P_Wave_assessment_Broad_Yes
  when
    grd1 : (P_Wave_Broad(II) ≥ 110 ∧ P_Wave_Broad(V1) ≥ 110) ∨
            Diphasic(II) = TRUE ∨
            Diphasic(V1) = TRUE
    grd2 : Heart_State = KO
  then
    act1 : Disease_step6 := LAE
  end

```



```

end

Event P_Wave_assessment_Broad_Yes_Check_LAE ≐
extends P_Wave_assessment_Broad_Yes_Check_LAE

when
  grd1 : (P_Wave_Broad(II) ≥ 110 ∧ P_Wave_Broad(V1) ≥ 110) ∨
          Diphasic(II) = TRUE ∨
          Diphasic(V1) = TRUE
  grd2 : Disease_step6 = LAE
  grd3 : Heart_State = KO
then
  act1 : Disease_step6 ∈ {mitral_stenosis, mitral_regurgitation,
                          LV_failure, dilated_cardiomyopathy}
end

Event LVH_Assessment ≐
LVH_Assessment

extends LVH_Assessment

any
  LVH_specificity    specificity in percentage
  sensitivity        sensitivity in percentage
  sex
where
  grd1 : (P_Wave_Broad(II) ≥ 110 ∧ P_Wave_Broad(V1) ≥ 110) ∨
          Diphasic(II) = TRUE ∨
          Diphasic(V1) = TRUE
  grd2 : Disease_step6 = LAE
  grd5 : sex ∈ {0, 1}
          o for men and 1 for women
  grd3 : ((S_Depth(V1) + R_Depth(V5)) > 35000
          ∨
          (S_Depth(V1) + R_Depth(V6)) > 35000)
          1mm = 1000 micrometer..... 1 assessment
  grd4 : ((R_Depth(aVL) + S_Depth(V1) ≥ 24000) ∧ sex = 0)
          ∨
          ((R_Depth(aVL) + S_Depth(V1) ≥ 18000) ∧ sex = 1)
          2 assessment
  grd6 : LVH_specificity = 90
          ∧
          sensitivity < 40
          1 and 2 assessment
  grd7 : Disease_step6 = LAE ⇒ LVH_specificity < 98
          3 assessment
  grd8 : (∀t.t ∈ LEADS ⇒ ST_elevation(t) = TRUE
          ∨
          Q_Normal_Status = FALSE))
          A or B : from step 8 development
  grd9 : (∀l1, k1.l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
          ((ST_elevation(l1) = FALSE ∨ ST_elevation(k1) = FALSE)
          ∨
          ∨

```

```

      ((ST_seg_ele(l1) < 1000 ∨ ST_seg_ele(k1) < 1000)
      ∧
      (Abnormal_Shaped_ST(l1) = FALSE ∨ Abnormal_Shaped_ST(k1) = FALSE)))
      ⇒ l1 ≠ k1))
grd10 : Asy_T_Inversion_strain(V5) = TRUE ∧
        Asy_T_Inversion_strain(V6) = TRUE ∧
        Asy_T_Inversion_strain(V4) = TRUE
grd11 : Heart_State = KO
grd12 : T_Normal_Status = FALSE
  then
    act1 : Disease_step6 := LVH_cause
  end

Event RVH_Assessment ≜
  RVH_Assessment

extends RVH_Assessment

any
  age    age od men or women
  aixs   axis for deviation

where
  grd1 : P_Wave_Peak(II) ≥ 3000
  grd2 : P_Wave_Peak(V1) ≥ 3000
  grd3 : Disease_step6 = RAE
  grd4 : R_Depth(V1) ≥ 7000 ∧ age > 30
          1 assessment
  grd5 : S_Depth(V5) ≥ 7000 ∨
          S_Depth(V6) ≥ 7000
          2 assessment
  grd6 : R_S_Ratio(V1) ≥ 100
          R_S_Ratio is multiply by 100 to remove the real no. constants... 3 assessment
  grd7 : R_S_Ratio(V5) ≤ 100
          ∨
          R_S_Ratio(V6) ≤ 100
          4 assessment
  grd8 : aixs ∈ 0 .. 360 ∧ aixs ≥ 110
          5 assessment
  grd9 : Disease_step2 ∉ {LBBB, RBBB}
  grd10 : QRS_Int < 120
  grd11 : (∀ t ∈ LEADS ⇒ ST_elevation(t) = TRUE
          ∨
          Q_Normal_Status = FALSE))

AorB : from_step8_development
        ∨
        (∀ l1, k1 · l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
        ((ST_elevation(l1) = FALSE ∨ ST_elevation(k1) = FALSE)
        ∨
        ((ST_seg_ele(l1) < 1000 ∨ ST_seg_ele(k1) < 1000)
        ∧
        (Abnormal_Shaped_ST(l1) = FALSE ∨ Abnormal_Shaped_ST(k1) = FALSE)))
        ⇒ l1 ≠ k1))

```

```

grd13 : Asy_T_Inversion_strain(V1) = TRUE ∧
        Asy_T_Inversion_strain(V2) = TRUE ∧
        Asy_T_Inversion_strain(V3) = TRUE
grd14 : Heart.State = KO
grd15 : T_Normal_Status = FALSE
    then
        act1 : Disease_step6 := RVH
    end
Event T_Wave_Assessment_Peaked_V123456 ≐
    T_Wave_Assessment
extends T_Wave_Assessment_Peaked_V123456
    when
        grd1 : Heart.State = KO
        grd2 : ∀l. l ∈ {V1, V2, V3, V4, V5, V6} ⇒ T_Wave_State(l) = Peaked
    then
        act1 : Disease_step8 := Hyperkalemia
    end
Event T_Wave_Assessment_Peaked_V12 ≐
extends T_Wave_Assessment_Peaked_V12
    when
        grd1 : R_Normal_Status = FALSE
        grd2 : T_Wave_State(V1) = Peaked ∧
              T_Wave_State(V2) = Peaked
        grd3 :
            ∨
            ((ST_elevation(l1) = FALSE ∧ ST_elevation(k1) = FALSE)
            ∨
            ((ST_seg_ele(l1) < 1000 ∧ ST_seg_ele(k1) < 1000)
            ∧
            (Abnormal_Shaped_ST(l1) = FALSE ∧ Abnormal_Shaped_ST(k1) = FALSE)))
            ⇒ l1 ≠ k1))
grd4 : ∀l. l ∈ LEADS ⇒ T_inversion(l) < 5000
        step 8 B
grd5 : T_Normal_Status = FALSE
    then
        act1 : Mice_State := normal_variant
    end
Event T_Wave_Assessment_Peaked_V12_MI ≐
    posterior MI using T wave assessment in LEADS V1 and V2
extends T_Wave_Assessment_Peaked_V12_MI
    when
        grd1 : T_Wave_State(V1) = Peaked ∧
              T_Wave_State(V2) = Peaked
        grd6 : Heart.State = KO

```

```

    grd2 :  $\vee$ 
      (( $\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
      ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
       $\vee$ 
      ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
       $\wedge$ 
      ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ )))
       $\Rightarrow l1 \neq k1$ )
grd3 :  $\forall l. l \in LEADS \Rightarrow T.inversion(l) > 5000$ 
grd4 :  $T.inversion.l.d(V2) = Localized \wedge$ 
       $T.inversion.l.d(V3) = Localized \wedge$ 
       $T.inversion.l.d(V4) = Localized \wedge$ 
       $T.inversion.l.d(V5) = Localized$ 
grd5 :  $T.inversion.l.d(II) = Localized \wedge$ 
       $T.inversion.l.d(III) = Localized \wedge$ 
       $T.inversion.l.d(aVF) = Localized$ 
grd7 :  $T.Normal.Status = FALSE$ 
  then
    act1 :  $Disease\_step8 := posterior\_MI$ 
  end
Event  $T.Wave\_Assessment\_Flat \hat{=}$ 
extends  $T.Wave\_Assessment\_Flat$ 
  when
    grd1 :  $\forall l. l \in LEADS \Rightarrow T.Wave.State(l) = Flat$ 
    grd4 :  $Heart.State = KO$ 
    grd2 :  $\vee$ 
      (( $\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
      ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
       $\vee$ 
      ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
       $\wedge$ 
      ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ )))
       $\Rightarrow l1 \neq k1$ )
  step 8 B
grd3 :  $\forall l. l \in LEADS \Rightarrow T.inversion(l) < 5000$ 
grd5 :  $T.Normal.Status = FALSE$ 
  then
    act1 :  $Disease\_step8 := Nonspecific\_ST.T.changes$ 
    act2 :  $Disease\_step8.B \in \{Cardiomyopathy, Electrolyte\_depletion, Alcohol, Myocarditis, Other\}$ 
  end
Event  $T.Wave\_Assessment\_Inverted\_Yes \hat{=}$ 
extends  $T.Wave\_Assessment\_Inverted\_Yes$ 
  when
    grd1 :  $\forall l. l \in LEADS \Rightarrow T.Wave.State(l) = Inverted$ 
    grd2 :  $\forall l. l \in LEADS \Rightarrow ST.elevation(l) = TRUE$ 
       $\vee$ 
       $Q.Normal.Status = FALSE$ 
    grd3 :  $Heart.State = KO$ 
  then

```

```

    act1 : Disease_step8 := {Definite_ischemia, Probable_ischemia, Digitalis_effect}
  end

Event T.Wave_Assessment_Inverted_No  $\hat{=}$ 
extends T.Wave_Assessment_Inverted_No

  when
    grd1 :  $\forall l. l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$ 
    grd2 :  $\forall l. l \in LEADS \Rightarrow ST\_elevation(l) = FALSE$ 
            $\vee$ 
            $Q\_Normal\_Status = TRUE$ 
    grd3 : Heart_State = KO
  then
    act1 : Disease_step8 := Nonspecific
  end

Event T.Wave_Assessment_Inverted_Yes_PM  $\hat{=}$ 
  PM - pulmonary embolism this disease is already defined in previous development.
extends T.Wave_Assessment_Inverted_Yes_PM

  when
    grd1 : P_Wave_Peak(II)  $\geq$  3000
    grd2 : P_Wave_Peak(V1)  $\geq$  3000
    grd3 : Disease_step6 = RAE
    grd4 :  $(\forall t. t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$ 
            $\vee$ 
            $Q\_Normal\_Status = FALSE)$ 
  then
    act1 : Disease_step6 := pulmonary_embolism
  end

  when
    A : step8 Heart_State = KO
    grd5 :
    grd5 :  $\vee$ 
            $(\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
            $(ST\_elevation(l1) = FALSE \wedge ST\_elevation(k1) = FALSE)$ 
            $\wedge$ 
            $((ST\_seg\_ele(l1) < 1000 \wedge ST\_seg\_ele(k1) < 1000)$ 
            $\vee$ 
            $(Abnormal\_Shaped\_ST(l1) = FALSE \wedge Abnormal\_Shaped\_ST(k1) = FALSE))$ 
            $\Rightarrow l1 \neq k1)$ 
    grd6 : Asy_T_Inversion_strain(V1) = TRUE  $\wedge$ 
           Asy_T_Inversion_strain(V2) = TRUE  $\wedge$ 
           Asy_T_Inversion_strain(V3) = TRUE
    grd8 : T_Normal_Status = FALSE
  then
    act1 : Disease_step6 := pulmonary_embolism
  end

Event T.Wave_Assessment_B  $\hat{=}$ 
  B for alternate method of T wave assessment
extends T.Wave_Assessment_B

  when
    grd1 :  $\forall l. l \in \{I, II, V3, V4, V5, V6\} \Rightarrow T\_Wave\_State\_B(l) = Upright$ 
    grd2 :  $T\_Wave\_State\_B(aVL) = Inverted\_B$ 
    grd3 :  $\forall l. l \in \{III, aVL, aVF, V1, V2\} \Rightarrow T\_Wave\_State\_B(l) = Variable$ 
  
```

```

then
  act1 : T_Normal_Status := TRUE
end

Event T_Wave_Assessment_B_DI  $\hat{=}$ 
  abnormal T wave ....in B ...DI(Definite Ischemia)

extends T_Wave_Assessment_B_DI

when
  grd1 :  $\forall l \cdot l \in \text{LEADS} \Rightarrow \text{T\_Wave\_State}(l) = \text{Inverted}$ 
  grd2 :  $\forall l \cdot l \in \text{LEADS} \Rightarrow \text{ST\_elevation}(l) = \text{TRUE}$ 
         $\vee$ 
        Q_Normal_Status = FALSE
  grd3 : T_Normal_Status = FALSE
        added in step-8 B
  grd5 : Heart_State = KO
  grd4 :  $\exists l, k \cdot l \in \text{LEADS} \wedge k \in \text{LEADS} \wedge$ 
         $((\text{ST\_seg\_ele}(l) \geq 1000 \wedge \text{ST\_seg\_ele}(k) \geq 1000) \vee$ 
         $(\text{ST\_elevation}(l) = \text{TRUE} \wedge \text{ST\_elevation}(k) = \text{TRUE}))$ 
         $\vee$ 
         $(\text{Abnormal\_Shaped\_ST}(l) = \text{TRUE} \wedge \text{Abnormal\_Shaped\_ST}(k) = \text{TRUE}))$ 
         $\wedge$ 
         $l \neq k$ 
        added in step-8 B

then
  act1 : Disease_step8 := Definite_ischemia
end

Event T_Inversion_Likely_Ischemia  $\hat{=}$ 
  probable Ischemia or Likly ischemia

extends T_Inversion_Likely_Ischemia

when
  grd1 :  $\forall l \cdot l \in \text{LEADS} \Rightarrow \text{T\_Wave\_State}(l) = \text{Inverted}$ 
  grd2 :  $\forall l \cdot l \in \text{LEADS} \Rightarrow \text{ST\_elevation}(l) = \text{TRUE}$ 
         $\vee$ 
        Q_Normal_Status = FALSE
  grd3 :  $\forall l \cdot l \in \text{LEADS} \Rightarrow \text{T\_inversion}(l) > 5000$ 
        1 mm= 1000
  grd4 :  $\vee$ 
         $(\forall l, k \cdot l \in \text{LEADS} \wedge k \in \text{LEADS} \wedge$ 
         $((\text{ST\_elevation}(l) = \text{FALSE} \vee \text{ST\_elevation}(k) = \text{FALSE}))$ 
         $\vee$ 
         $((\text{ST\_seg\_ele}(l) < 1000 \vee \text{ST\_seg\_ele}(k) < 1000)$ 
         $\wedge$ 
         $(\text{Abnormal\_Shaped\_ST}(l) = \text{FALSE} \vee \text{Abnormal\_Shaped\_ST}(k) = \text{FALSE})))$ 
         $\Rightarrow l \neq k$ )
  grd5 : T_inversion_l.d(V2) = Localized  $\wedge$ 
        T_inversion_l.d(V3) = Localized  $\wedge$ 
        T_inversion_l.d(V4) = Localized  $\wedge$ 
        T_inversion_l.d(V5) = Localized
  grd6 : T_inversion_l.d(II) = Localized  $\wedge$ 
        T_inversion_l.d(III) = Localized  $\wedge$ 
        T_inversion_l.d(aVF) = Localized
  b. of Deep inversion  $i$  5mm

```

```

grd7 : Heart.State = KO
grd8 : T_Normal.Status = FALSE
    then
        act1 : Disease_step8 := Probable_ischemia
    end
Event T_Inversion_Diffuse_B  $\hat{=}$ 
    Step 8 B for c.
extends T_Inversion_Diffuse_B
    when
        grd1 :  $\bigvee$ 
            (( $\forall l1, k1.l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
            ((ST_elevation(l1) = FALSE  $\vee$  ST_elevation(k1) = FALSE)
             $\vee$ 
            ((ST_seg_ele(l1) < 1000  $\vee$  ST_seg_ele(k1) < 1000)
             $\wedge$ 
            (Abnormal_Shaped_ST(l1) = FALSE  $\vee$  Abnormal_Shaped_ST(k1) = FALSE)))
             $\Rightarrow l1 \neq k1$ ))
grd2 :  $\forall l.l \in LEADS \Rightarrow T.inversion(l) > 5000$ 
grd3 :  $\forall l.l \in LEADS \Rightarrow T.inversion.l.d(l) = Diffuse$ 
grd4 : Heart.State = KO
grd5 : T_Normal.Status = FALSE
    then
        act1 : Disease_step8_B : $\in$  {Cardiomyopathy, other_nonspecific}
    end
Event Axis_Assessment_QRS_upright_Yes  $\hat{=}$ 
    when
        grd1 : QRS_Axis_State(I) = D_Upright  $\wedge$ 
            QRS_Axis_State(aVF) = D_Upright
    then
        act1 : minAngle : $\in$  {0, -30}
        act2 : maxAngle : $\in$  {110, 90}
    end
Event Axis_Assessment_QRS_upright_No  $\hat{=}$ 
    when
        grd1 : (QRS_Axis_State(I)  $\neq$  D_Upright  $\vee$ 
            QRS_Axis_State(aVF)  $\neq$  D_Upright)
    then
        act1 : minAngle : $\in$  {-30, 110}
        act2 : maxAngle : $\in$  {-90, 180}
    end
END

```

An Event-B Specification of Step9_Axis_Assessment_Ref1
Generated Date: 25 Nov 2010 @ 03:39:44 PM

MACHINE Step9_Axis_Assessment_Ref1

REFINES Step9_Axis_Assessment

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx, Step8_ctx, Step9

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
Small_R_QS A small R or QS wave in V1 and V2
Slurred_S_duration Slurred S duration
Delta_Wave Delta Wave
Disease_step3
ST_elevation ST segment elevation (Coved or Saddle-back)
Epsilon_Wave Epsilon Wave or (a terminal notch in the QRS)
ST_seg_ele ST segment for elevation 1mm=0.1mV
Disease_step4
Q_Width Q wave width
Q_Depth Q wave depth
Q_Normal_Status Q wave normal or abnormal
Age_of_Inf Age of Infarct
Disease_step5
Mice_State
R_Depth R wave depth or height (also use in Step 7)
R_Normal_Status R wave normal or abnormal
Q_Wave_State Q wave states for all LEADS
P_Wave_Peak function to estimate the peak of LEADS signal
Disease_step6
PP_Interval
RR_Interval
Diphasic
P_Wave_Broad
S_Depth S wave depth or height

R_S_Ratio R wave and S wave Ratio function
T_Wave_State T wave patterns...
Disease_step8
T_Wave_State_B B for alternative method of T wave assessment
T_Normal_Status T wave normal or abnormal
Abnormal_Shaped_ST
Asy_T_Inversion_strain Asymmetric T wave Inversion strain pattern
T_inversion Deep T wave inversion
T_inversion_l_d T inversion Localized and Diffuse
Disease_step8_B
QRS_Axis_State QRS Axis Direction
minAngle min. value of angle of Axis in degree
maxAngle max. value of angle of Axis in degree
Axis_Devi Axis Deviation in LEADS...
Disease_step9
ST_depression

INVARIANTS

inv1 : $Axis_Devi \in Axis_deviation$
inv2 : $Disease_step9 \in Disease_Codes_Step9$
inv3 : $Disease_step9 \in \{LPFB, Dextrocardia, NV_MSEC\} \wedge maxAngle = 180 \wedge minAngle = 110 \Rightarrow Heart_State = KO$
inv4 : $Disease_step9 \in \{LAFB, MSCHD, Some_Form_VT, ED_OC\} \wedge maxAngle = -90 \wedge minAngle = -30 \Rightarrow Heart_State = KO$

EVENTS

Initialisation

extended

begin

act1 : $RR_Int_equidistant : \in LEADS \rightarrow BOOL$
act2 : $PP_Int_equidistant : \in LEADS \rightarrow BOOL$
act3 : $P_Positive : \in LEADS \rightarrow BOOL$
act4 : $Sinus := No$
act5 : $PP_Interval : \in LEADS \rightarrow \mathbb{N}$
act6 : $RR_Interval : \in LEADS \rightarrow \mathbb{N}$
act7 : $Heart_Rate : \in 1..300$
act8 : $Heart_State := KO$
act9 : $PR_Int := 120$
act10 : $Disease_step2 := NDS2$
act11 : $QRS_Int := 50$
act12 : $Notched_R : \in LEADS \rightarrow BOOL$
act13 : $Small_R_QS : \in LEADS \rightarrow BOOL$
act14 : $Slurred_S_duration : \in LEADS \rightarrow \mathbb{N}_1$
act15 : $M_Shape_Complex : \in LEADS \rightarrow BOOL$
act16 : $Slurred_S : \in LEADS \rightarrow BOOL$
act17 : $ST_elevation : \in LEADS \rightarrow BOOL$
act18 : $Epsilon_Wave : \in LEADS \rightarrow BOOL$

```

act19 : Delta_Wave := 0
act20 : Disease_step3 := NDS3
act21 : ST_seg_ele :∈ LEADS → ℕ
act22 : Disease_step4 := NDS4
act57 : ST_depression :∈ LEADS → ℕ
act23 : Q_Width :∈ LEADS → ℕ
act24 : Q_Depth :∈ LEADS → ℕ
act25 : Q_Normal_Status := FALSE
act26 : Mice_State := NMS
act27 : R_Depth :∈ LEADS → ℕ
act28 : R_Normal_Status := FALSE
act29 : Q_Wave_State :∈ LEADS → BOOL
act30 : Age_of_Inf :∈ Age_of_Infarct
act31 : Disease_step5 := NDS5
act32 : Diphasic :∈ LEADS → BOOL
act33 : P_Wave_Broad :∈ LEADS → ℕ
act34 : P_Wave_Peak :∈ LEADS → ℕ
act35 : Disease_step6 := NDS6
act36 : S_Depth :∈ LEADS → ℕ
act37 : R_S_Ratio :∈ LEADS → ℕ
act38 : T_Wave_State :∈ LEADS → T_State
act39 : Disease_step8 := NDS8
act40 : Abnormal_Shaped_ST :∈ LEADS → BOOL
act41 : Asy_T_Inversion_strain :∈ LEADS → BOOL
act43 : T_inversion_l_d :∈ LEADS → T_State_l_d
act42 : T_inversion :∈ LEADS → ℕ
act44 : Disease_step8_B := NDS8B
act45 : T_Wave_State_B :∈ LEADS → T_State_B
act46 : T_Normal_Status := FALSE
act47 : QRS_Axis_State :∈ LEADS → QRS_directions
act48 : minAngle := 0
act49 : maxAngle := 0
act50 : Axis_Devi := ND
act51 : Disease_step9 := NDS9

```

end

Event *Rhythm_test_TRUE* $\hat{=}$
Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

any

rate

where

```

grd1 : (∃ l·l ∈ {II, V1, V2} ∧ PP_Int.equidistant(l) = TRUE ∧
        RR_Int.equidistant(l) = TRUE ∧
        RR_Interval(l) = PP_Interval(l))
        ∧
        P_Positive(II) = TRUE

```

grd4 : rate ∈ 60..100
60..100 is the range of normal heart rate

```

grd5 : PR_Int ≤ 200
      Heart is Normal if PR ≤ 200 QRS_Int < 120
      Heart is Normal if QRS < 120
grd7 : Disease_step2 = NDS2
grd8 : Disease_step3 = NDS3
grd9 : Disease_step4 = NDS4
grd10 : Disease_step5 = NDS5
grd11 : Disease_step6 = NDS6
grd12 : Disease_step8 = NDS8
grd13 : Disease_step8_B = NDS8B
grd14 : Disease_step9 = NDS9
then
  act1 : Sinus := Yes
  act2 : Heart_Rate := rate
  act3 : Heart_State := OK
end
Event Rhythm_test_FALSE ≐
  Abnormal Rhythm with Rate
extends Rhythm_test_FALSE
any
  rate
where
  grd1 : (∀l. l ∈ {II, V1, V2} ⇒ PP_Int_equidistant(l) = FALSE ∨
          RR_Int_equidistant(l) = FALSE ∨
          RR_Interval(l) ≠ PP_Interval(l))
          ∨
          P_Positive(II) = FALSE
  grd2 : rate ∈ 1..300
then
  act1 : Sinus := No
  act2 : Heart_Rate := rate
  act3 : Heart_State := KO
end
Event Rhythm_test_TRUE_Rate ≐
  Sinus Rhythm with abnormal Rate
extends Rhythm_test_TRUE_Rate
any
  rate
where
  grd1 : (∃l. l ∈ {II, V1, V2} ∧ PP_Int_equidistant(l) = TRUE ∧
          RR_Int_equidistant(l) = TRUE ∧
          RR_Interval(l) = PP_Interval(l))
          ∧
          P_Positive(II) = TRUE
  grd5 : rate ∈ 1..300 \ 60..100
          60..100 is the range of normal heart rate, so rest of no. is abnormal
  grd6 : Disease_step3 = WPW_Syndrome ∨ Disease_step3 = Brugada_Syndrome ∨
          Disease_step3 = RV_Dysplasia ∨ Disease_step3 = IVCD

```

```

    then
        act1 : Sinus := Yes
        act2 : Heart_Rate := rate
        act3 : Heart_State := KO
    end

Event PR_Test ≐
    PR Interval Test

extends PR_Test

any
    pr
where
    grd1 : pr ∈ 120 .. 220
           time interval in (ms.)
    grd2 : pr > 200
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
then
    act1 : PR_Int := pr
    act2 : Disease_step2 := First_degree_AV_Block
end

Event QRS_Test_LBBB ≐
    QRS Complex Interval Test

extends QRS_Test_LBBB

any
    qrs
where
    grd1 : qrs ∈ 50 .. 150
    grd2 : qrs ≥ 120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : Notched_R(I) = TRUE ∧
           Notched_R(V5) = TRUE ∧
           Notched_R(V6) = TRUE
           Right Bundle Branch Block (RBBB)
    grd6 : Small_R_QS(V1) = TRUE ∧
           Small_R_QS(V2) = TRUE
    grd7 : Q_Wave_State(V1) = TRUE ∧
           Q_Wave_State(V2) = TRUE ∧
           Q_Wave_State(V3) = TRUE ∧
           Q_Wave_State(V4) = TRUE
           from step 5
    grd8 : R_Normal_Status = FALSE
           from step 5
    grd9 : Axis_Devi = LAD ∧
           minAngle = -30 ∧
           maxAngle = -90
then

```

```

    act1 : QRS_Int := qrs
    act2 : Disease_step2 := LBBB
  end

Event QRS_Test_RBBB  $\hat{=}$ 
  Right Bundle Branch Block (RBBB)

extends QRS_Test_RBBB

  any
    qrs
  where
    grd1 : qrs  $\in$  50 .. 150
    grd2 : qrs  $\geq$  120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : M.Shape_Complex(V1) = TRUE  $\wedge$ 
           M.Shape_Complex(V2) = TRUE
    grd7 : Slurred_S(I) = TRUE  $\wedge$ 
           Slurred_S(V5) = TRUE  $\wedge$ 
           Slurred_S(V6) = TRUE
    grd8 : Slurred_S.duration(I) > 40  $\wedge$ 
           Slurred_S.duration(V5) > 40  $\wedge$ 
           Slurred_S.duration(V6) > 40
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := RBBB
  end

Event QRS_Test_Atypical_RLBBB_WPW_Syndrome  $\hat{=}$ 
  QRS Test for Atypical LBBB RBBB

extends QRS_Test_Atypical_RLBBB_WPW_Syndrome

  any
    sympt
    d_wave
    exmi
  where
    grd1 : QRS_Int  $\geq$  110
    grd2 : sympt = A_RBBB  $\vee$  sympt = A_LBBB
    grd3 : d_wave  $\in$   $\mathbb{N}$ 
    grd4 : (d_wave + PR_Int)  $\leq$  120
           Delta Wave + PR  $\leq$  120 Heart_State = KO
    grd5grd6 : Disease_step4 = Acute_inferior_MI
    grd7 : exmi  $\in$  Mice_State5  $\wedge$  exmi = Exclude_Mimics_MI
  then
    act2 : Delta_Wave := d_wave
    act3 : Disease_step3 := WPW_Syndrome
  end

Event QRS_Test_Atypical_RBBB_Brugada_Syndrome  $\hat{=}$ 
  Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

```

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

 sympt
 dis

where

 grd1 : sympt = A_RBBB
 grd2 : Heart_State = KO
 grd3 : QRS_Int \geq 110
 grd4 : Slurred_S(V5) = FALSE \wedge
 Slurred_S(V6) = FALSE
 grd5 : dis \in Disease_Codes_Step3 \ {WPW_Syndrome, NDS3}
 grd6 : ST_elevation(V1) = TRUE \wedge
 ST_elevation(V2) = TRUE
 grd7 : Sinus = Yes

then

 act1 : Disease_step3 := Brugada_Syndrome

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\hat{=}$
Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

 sympt
 dis

where

 grd1 : sympt = A_RBBB
 grd2 : Heart_State = KO
 grd3 : QRS_Int \geq 110
 grd4 : dis \in Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, NDS3}
 grd5 : Epsilon_Wave(V1) = TRUE \wedge
 Epsilon_Wave(V3) = TRUE

then

 act1 : Disease_step3 := RV_Dysplasia

end

Event *QRS_Test_Atypical_RBBB_IVCD* $\hat{=}$
IVCD diagnosis

extends *QRS_Test_Atypical_RBBB_IVCD*

any

 dis

where

 grd1 : QRS_Int \geq 110
 grd2 : dis \in Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, NDS3}
 grd3 : Heart_State = KO

then

 act1 : Disease_step3 := IVCD

end

```

Event ST_seg_elevation_YES  $\hat{=}$ 
  ST segment elevation...

extends ST_seg_elevation_YES

  when
    grd1 : Heart.State = KO
    grd2 : Sinus = Yes
    grd3 :  $\vee$ 
      (( $\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
      (ST_elevation(l1) = TRUE  $\wedge$  ST_elevation(k1) = TRUE)
       $\wedge$ 
      (ST_seg_ele(l1)  $\geq$  1000  $\wedge$  ST_seg_ele(k1)  $\geq$  1000)
       $\wedge$  l1  $\neq$  k1
       $\wedge$ 
      (
        (l1 = V1  $\wedge$  k1 = V2)  $\vee$ 
        (l1 = V2  $\wedge$  k1 = V3)  $\vee$ 
        (l1 = V3  $\wedge$  k1 = V4)  $\vee$ 
        (l1 = V4  $\wedge$  k1 = V5)  $\vee$ 
        (l1 = V5  $\wedge$  k1 = V6)
      )
    ))
  grd4 : Disease_step4  $\in$  {Acute_inferior_MI, Acute_anterior_MI}
  then
    act1 : Disease_step4 := STEMI
  end

Event ST_seg_elevation_NOTCKMB_Yes  $\hat{=}$ 
  Troponin or CK-MB positive YES

extends ST_seg_elevation_NOTCKMB_Yes

  when
    grd1 : Heart.State = KO
    grd2 : Sinus = Yes
    grd3 :  $\vee$ 
      ( $\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$ 
      (ST_elevation(l1) = FALSE  $\wedge$  ST_seg_ele(l1) < 1000))
  grd4 :  $\exists l, k \cdot l \in \text{LEADS} \wedge k \in \text{LEADS} \wedge$ 
    (ST_depression(l)  $\geq$  1000  $\wedge$  ST_depression(k)  $\geq$  1000)
     $\wedge$  l  $\neq$  k
  grd5 : Disease_step4  $\in$  {Troponin, CK_MB}
  then
    act1 : Disease_step4 := Non_STEMI
  end

Event ST_seg_elevation_NO_TCKMB_No  $\hat{=}$ 
  Troponin or CK-MB positive No

extends ST_seg_elevation_NO_TCKMB_No

  when
    grd1 : Heart.State = KO
    grd2 : Sinus = Yes

```

```

    grd3 :  $\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$ 
      ( $ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000$ )
grd4 :  $\exists l, k \cdot l \in LEADS \wedge k \in LEADS \wedge$ 
      ( $ST\_depression(l) \geq 1000 \wedge ST\_depression(k) \geq 1000$ 
       $\wedge l \neq k$ )
grd5 : Disease_step4  $\notin$  {Troponin, CK_MB}
grd6 :  $\forall l \cdot l \in LEADS \Rightarrow T\_inversion(l) < 5000$ 
grd7 : T_Normal_Status = FALSE
  then
    act1 : Disease_step4 := Ischemia
  end

Event Q_Assessment_Normal  $\hat{=}$ 
  Q wave assessment normal

extends Q_Assessment_Normal

  when
    grd1 : Q_Width(II) < 40  $\wedge$  Q_Depth(II)  $\leq$  3000  $\wedge$ 
      Q_Width(aVF) < 40  $\wedge$  Q_Depth(aVF)  $\leq$  3000  $\wedge$ 
      Q_Width(aVL) < 40
      1000 micrometer = 1 millimeter
    grd2 : Q_Width(III)  $\leq$  40  $\wedge$  Q_Depth(III)  $\leq$  7000  $\wedge$  Q_Depth(aVL)  $\leq$  7000
    grd3 : Q_Depth(I) < 40  $\wedge$  Q_Depth(I)  $\leq$  1500
  then
    act1 : Q_Normal_Status := TRUE
  end

Event Q_Assessment_Abnormal_AMI  $\hat{=}$ 
  Q wave assessment abnormal for anterolateral MI (AMI)

extends Q_Assessment_Abnormal_AMI

  when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :  $\forall$ 
      ( $(\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
      ( $ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE$ )
       $\wedge$ 
      ( $ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000$ )
       $\wedge l1 \neq k1$ 
       $\wedge$ 
      (
        ( $l1 = V1 \wedge k1 = V2$ )  $\vee$ 
        ( $l1 = V2 \wedge k1 = V3$ )  $\vee$ 
        ( $l1 = V3 \wedge k1 = V4$ )  $\vee$ 
        ( $l1 = V4 \wedge k1 = V5$ )  $\vee$ 
        ( $l1 = V5 \wedge k1 = V6$ )
      )
      )
      )
    grd4 : Q_Width(V5)  $\geq$  40  $\wedge$  Q_Depth(V5) > 3000  $\wedge$ 
      Q_Width(V6)  $\geq$  40  $\wedge$  Q_Depth(V6) > 3000
    grd5 : Q_Width(aVL)  $\geq$  40  $\wedge$  Q_Depth(aVL) > 7000

```



```

grd6 : Q_Depth(I) ≥ 40 ∧ Q_Depth(I) > 1500
grd7 : Q_Normal_Status = FALSE
    then
        act1 : Disease_step4 := Acute_anterior_MI
    end

Event Q_Assessment_Abnormal_IMI ≐
    Q wave assessment abnormal for inferior MI (IMI)

extends Q_Assessment_Abnormal_IMI

when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :
        ∨
        ((∃ l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
        (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
        ∧
        (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
        ∧ l1 ≠ k1
        ∧
        (
        (l1 = V1 ∧ k1 = V2) ∨
        (l1 = V2 ∧ k1 = V3) ∨
        (l1 = V3 ∧ k1 = V4) ∨
        (l1 = V4 ∧ k1 = V5) ∨
        (l1 = V5 ∧ k1 = V6)
        )
        ))
grd4 : Q_Width(II) ≥ 40 ∧ Q_Depth(II) > 3000 ∧
    Q_Width(III) > 40 ∧ Q_Depth(III) > 7000 ∧
    Q_Width(aVF) ≥ 40 ∧ Q_Depth(aVF) > 3000
grd5 : Q_Normal_Status = FALSE
    then
        act1 : Disease_step4 := Acute_inferior_MI
    end

Event Determine_Age_of_Infarct ≐
    Determine_Age_of_Infarct

extends Determine_Age_of_Infarct

when
    grd1 : Disease_step4 = Acute_inferior_MI
        ∨
        Disease_step5 ∈ {anterior_MI, LVH, emphysema}
        ∨
        Mice_State = Exclude_Mimics_MI
        ∨
        Disease_step2 = LBBB

    then
        act1 : Age_of_Inf := {recent, old, indeterminate}
    end

Event Exclude_Mimics ≐
    Exclude_Mimics

extends Exclude_Mimics

```

```

any
  exmi
where
  grd1 : Disease_step4 = Acute_inferior_MI
  grd2 : exmi ∈ Mice_State5 ∧ exmi = Exclude_Mimics_MI
then
  act1 : Disease_step5 := Hypertrophic_cardiomyopathy
  act2 : Mice_State := borderline_Qs
end

Event R_Assessment_Normal ≐
  Q wave assessment normal

extends R_Assessment_Normal

any
  age
where
  grd1 : R.Depth(V1) ≥ 0 ∧ R.Depth(V1) ≤ 6000 ∧ age > 30
    1000 micrometer = 1 millimeter
  grd2 : R.Depth(V2) > 200 ∧ R.Depth(V2) ≤ 12000
  grd3 : R.Depth(V2) ≥ 1000 ∧ R.Depth(V2) ≤ 24000
then
  act1 : R.Normal_Status := TRUE
end

Event R_Assessment_Abnormal ≐

extends R_Assessment_Abnormal

when
  grd1 : R.Normal_Status = FALSE
then
  act1 : Mice_State ∈ {late_transition, normal_variant}
end

Event R_Q_Assessment_R_Abnormal_V1234 ≐
  R wave abnormal , pathologic Q waves consider in V1-V4

extends R_Q_Assessment_R_Abnormal_V1234

when
  grd1 : R.Normal_Status = FALSE
  grd2 : Q_Wave_State(V1) = TRUE ∧
    Q_Wave_State(V2) = TRUE ∧
    Q_Wave_State(V3) = TRUE ∧
    Q_Wave_State(V4) = TRUE
  grd3 : Heart_State = KO
then
  act1 : Disease_step5 ∈ {anterior_MI, LVH, emphysema}
  act2 : Mice_State := Exclude_Mimics_MI
end

```

```

Event R_Q_Assessment_R_Abnormal_V56  $\hat{=}$ 
    R wave abnormal , pathologic Q waves consider in V5-V6
refines R_Q_Assessment_R_Abnormal_V56
    when
        grd1 : Q_Wave_State(V5) = TRUE  $\wedge$ 
                Q_Wave_State(V6) = TRUE
        grd2 : Heart_State = KO
    then
        act1 : Disease_step5 := Hypertrophic_cardiomyopathy
    end
Event P_Wave_assessment_Peaked_Broad_No  $\hat{=}$ 
extends P_Wave_assessment_Peaked_Broad_No
    when
        grd1 : (P_Wave_Peak(II) < 3000  $\wedge$ 
                P_Wave_Peak(V1) < 3000)
                 $\vee$ 
                (P_Wave_Broad(II) < 110  $\wedge$  P_Wave_Broad(V1) < 110)  $\vee$ 
                Diphasic(II) = FALSE  $\vee$ 
                Diphasic(V1) = FALSE
    then
        act1 : Disease_step6 := NDS6
    end
Event P_Wave_assessment_Peaked_Yes  $\hat{=}$ 
extends P_Wave_assessment_Peaked_Yes
    when
        grd1 : P_Wave_Peak(II)  $\geq$  3000
        grd2 : P_Wave_Peak(V1)  $\geq$  3000
        grd3 : Heart_State = KO
    then
        act1 : Disease_step6 := RAE
    end
Event P_Wave_assessment_Peaked_Yes_Check_RAE  $\hat{=}$ 
extends P_Wave_assessment_Peaked_Yes_Check_RAE
    when
        grd1 : P_Wave_Peak(II)  $\geq$  3000
        grd2 : P_Wave_Peak(V1)  $\geq$  3000
        grd3 : Disease_step6 = RAE
        grd4 : Heart_State = KO
    then
        act1 : Disease_step6 := RV_strain
    end
Event P_Wave_assessment_Broad_Yes  $\hat{=}$ 
extends P_Wave_assessment_Broad_Yes

```

```

when
    grd1 : (P_Wave_Broad(II) ≥ 110 ∧ P_Wave_Broad(V1) ≥ 110) ∨
            Diphasic(II) = TRUE ∨
            Diphasic(V1) = TRUE
    grd2 : Heart_State = KO
then
    act1 : Disease_step6 := LAE
end

Event P_Wave_assessment_Broad_Yes_Check_LAE ≐
extends P_Wave_assessment_Broad_Yes_Check_LAE

when
    grd1 : (P_Wave_Broad(II) ≥ 110 ∧ P_Wave_Broad(V1) ≥ 110) ∨
            Diphasic(II) = TRUE ∨
            Diphasic(V1) = TRUE
    grd2 : Disease_step6 = LAE
    grd3 : Heart_State = KO
then
    act1 : Disease_step6 ∈ {mitral_stenosis, mitral_regurgitation,
                            LV_failure, dilated_cardiomyopathy}
end

Event LVH_Assessment ≐
LVH_Assessment

extends LVH_Assessment

any
    LVH_specificity    specificity in percentage
    sensitivity        sensitivity in percentage
    sex

where
    grd1 : (P_Wave_Broad(II) ≥ 110 ∧ P_Wave_Broad(V1) ≥ 110) ∨
            Diphasic(II) = TRUE ∨
            Diphasic(V1) = TRUE
    grd2 : Disease_step6 = LAE
    grd5 : sex ∈ {0, 1}
            o for men and 1 for women
    grd3 : ((S_Depth(V1) + R_Depth(V5)) > 35000
            ∨
            (S_Depth(V1) + R_Depth(V6)) > 35000)
            1mm = 1000 micrometer..... 1 assessment
    grd4 : ((R_Depth(aVL) + S_Depth(V1) ≥ 24000) ∧ sex = 0)
            ∨
            ((R_Depth(aVL) + S_Depth(V1) ≥ 18000) ∧ sex = 1)
            2 assessment
    grd6 : LVH_specificity = 90
            ∧
            sensitivity < 40
            1 and 2 assessment
    grd7 : Disease_step6 = LAE ⇒ LVH_specificity < 98
            3 assessment

```

```

    grd8 :      ( $\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$ 
                 $\vee$ 
                 $Q\_Normal\_Status = FALSE$ ))
    A or B : from step 8 development
    grd9 :       $\vee$ 
    ( $\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
    ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
     $\vee$ 
    ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
     $\wedge$ 
    ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ ))
     $\Rightarrow l1 \neq k1$ )
grd10 : Asy_T_Inversion_strain(V5) = TRUE  $\wedge$ 
        Asy_T_Inversion_strain(V6) = TRUE  $\wedge$ 
        Asy_T_Inversion_strain(V4) = TRUE
grd11 : Heart.State = KO
grd12 : T_Normal.Status = FALSE
grd13 : Axis.Devi = LAD  $\wedge$ 
        minAngle = -30  $\wedge$ 
        maxAngle = -90
then
    act1 : Disease_step6 := LVH_cause
end

Event RVH_Assessment  $\hat{=}$ 
    RVH_Assessment

extends RVH_Assessment

any
    age    age od men or women
    aixs   axis for deviation

where
    grd1 : P.Wave.Peak(II)  $\geq$  3000
    grd2 : P.Wave.Peak(V1)  $\geq$  3000
    grd3 : Disease_step6 = RAE
    grd4 : R.Depth(V1)  $\geq$  7000  $\wedge$  age > 30
           1 assessment
    grd5 : S.Depth(V5)  $\geq$  7000  $\vee$ 
           S.Depth(V6)  $\geq$  7000
           2 assessment
    grd6 : R.S.Ratio(V1)  $\geq$  100
           R.S Ratio is multiply by 100 to remove the real no. constants... 3 assessment
    grd7 : R.S.Ratio(V5)  $\leq$  100
            $\vee$ 
           R.S.Ratio(V6)  $\leq$  100
           4 assessment
    grd8 : aixs  $\in$  0 .. 360  $\wedge$  aixs  $\geq$  110
           5 assessment
    grd9 : Disease_step2  $\notin$  {LBBB, RBBB}
    grd10 : QRS_Int < 120
    grd11 :      ( $\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$ 
                 $\vee$ 
                 $Q\_Normal\_Status = FALSE$ ))

```

```

AorB : from_step8development
      ∨
      (∀l1, k1. l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
      ((ST_elevation(l1) = FALSE ∨ ST_elevation(k1) = FALSE)
      ∨
      ((ST_seg_ele(l1) < 1000 ∨ ST_seg_ele(k1) < 1000)
      ∧
      (Abnormal_Shaped_ST(l1) = FALSE ∨ Abnormal_Shaped_ST(k1) = FALSE)))
      ⇒ l1 ≠ k1))
grd13 : Asy_T_Inversion_strain(V1) = TRUE ∧
      Asy_T_Inversion_strain(V2) = TRUE ∧
      Asy_T_Inversion_strain(V3) = TRUE
grd14 : Heart.State = KO
grd15 : T_Normal_Status = FALSE
grd16 : Axis_Devi = RAD ∧
      minAngle = 110 ∧
      maxAngle = 180
      then
        act1 : Disease_step6 := RVH
      end

Event T_Wave_Assessment_Peaked_V123456 ≐
      T_Wave_Assessment

extends T_Wave_Assessment_Peaked_V123456

when
  grd1 : Heart.State = KO
  grd2 : ∀l. l ∈ {V1, V2, V3, V4, V5, V6} ⇒ T.Wave.State(l) = Peaked
then
  act1 : Disease_step8 := Hyperkalemia
end

Event T_Wave_Assessment_Peaked_V12 ≐

extends T_Wave_Assessment_Peaked_V12

when
  grd1 : R_Normal_Status = FALSE
  grd2 : T.Wave.State(V1) = Peaked ∧
        T.Wave.State(V2) = Peaked
  grd3 :
    ∨
    (∀l1, k1. l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
    ((ST_elevation(l1) = FALSE ∨ ST_elevation(k1) = FALSE)
    ∨
    ((ST_seg_ele(l1) < 1000 ∨ ST_seg_ele(k1) < 1000)
    ∧
    (Abnormal_Shaped_ST(l1) = FALSE ∨ Abnormal_Shaped_ST(k1) = FALSE)))
    ⇒ l1 ≠ k1))
grd4 : ∀l. l ∈ LEADS ⇒ T.inversion(l) < 5000
      step 8 B
grd5 : T_Normal_Status = FALSE
grd6 :
  ∨
  (Axis_Devi = RAD ∧
  minAngle = 110 ∧
  maxAngle = 180)

```

```

then
    act1 : Mice_State := normal_variant
end

Event T_Wave_Assessment_Peaked_V12_MI  $\hat{=}$ 
    posterior MI using T wave assessment in LEADS V1 and V2

extends T_Wave_Assessment_Peaked_V12_MI

when
    grd1 : T.Wave_State(V1) = Peaked  $\wedge$ 
            T.Wave_State(V2) = Peaked
    grd6 : Heart_State = KO
    grd2 :  $\vee$ 
            (( $\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
              ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
               $\vee$ 
              ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
               $\wedge$ 
              ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ )))
               $\Rightarrow l1 \neq k1$ ))
grd3 :  $\forall l \cdot l \in LEADS \Rightarrow T.inversion(l) > 5000$ 
grd4 : T.inversion_l.d(V2) = Localized  $\wedge$ 
            T.inversion_l.d(V3) = Localized  $\wedge$ 
            T.inversion_l.d(V4) = Localized  $\wedge$ 
            T.inversion_l.d(V5) = Localized
grd5 : T.inversion_l.d(II) = Localized  $\wedge$ 
            T.inversion_l.d(III) = Localized  $\wedge$ 
            T.inversion_l.d(aVF) = Localized
grd7 : T.Normal_Status = FALSE
    then
        act1 : Disease_step8 := posterior_MI
    end

Event T_Wave_Assessment_Flat  $\hat{=}$ 

extends T_Wave_Assessment_Flat

when
    grd1 :  $\forall l \cdot l \in LEADS \Rightarrow T.Wave\_State(l) = Flat$ 
    grd4 : Heart_State = KO
    grd2 :  $\vee$ 
            (( $\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
              ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
               $\vee$ 
              ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
               $\wedge$ 
              ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ )))
               $\Rightarrow l1 \neq k1$ ))
    step 8 B
grd3 :  $\forall l \cdot l \in LEADS \Rightarrow T.inversion(l) < 5000$ 
grd5 : T.Normal_Status = FALSE
    then
        act1 : Disease_step8 := Nonspecific_ST_T_changes
        act2 : Disease_step8.B  $\in$  {Cardiomyopathy, Electrolyte_depletion, Alcohol, Myocarditis, Other}

```

```

    end

Event T_Wave_Assessment_Inverted_Yes ≐
extends T_Wave_Assessment_Inverted_Yes

when
    grd1 : ∀l.1 ∈ LEADS ⇒ T_Wave_State(1) = Inverted
    grd2 : ∀l.1 ∈ LEADS ⇒ ST_elevation(1) = TRUE
            ∨
            Q_Normal_Status = FALSE
    grd3 : Heart_State = KO
then
    act1 : Disease_step8 ∈ {Definite_ischemia, Probable_ischemia, Digitalis_effect}
end

Event T_Wave_Assessment_Inverted_No ≐
extends T_Wave_Assessment_Inverted_No

when
    grd1 : ∀l.1 ∈ LEADS ⇒ T_Wave_State(1) = Inverted
    grd2 : ∀l.1 ∈ LEADS ⇒ ST_elevation(1) = FALSE
            ∨
            Q_Normal_Status = TRUE
    grd3 : Heart_State = KO
then
    act1 : Disease_step8 := Nonspecific
end

Event T_Wave_Assessment_Inverted_Yes_PM ≐
    PM - pulmonary embolism this disease is already defined in previous development.
extends T_Wave_Assessment_Inverted_Yes_PM

when
    grd1 : P_Wave_Peak(II) ≥ 3000
    grd2 : P_Wave_Peak(V1) ≥ 3000
    grd3 : Disease_step6 = RAE
    grd4 : (∀t.t ∈ LEADS ⇒ ST_elevation(t) = TRUE
            ∨
            Q_Normal_Status = FALSE))

A : step8 Heart_State = KO
grd5 : (∀l1, k1.l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
        (ST_elevation(l1) = FALSE ∧ ST_elevation(k1) = FALSE)
        ∧
        ((ST_seg_ele(l1) < 1000 ∧ ST_seg_ele(k1) < 1000)
        ∨
        (Abnormal_Shaped_ST(l1) = FALSE ∧ Abnormal_Shaped_ST(k1) = FALSE))
        ⇒ l1 ≠ k1))
grd6 : Asy_T_Inversion_strain(V1) = TRUE ∧
        Asy_T_Inversion_strain(V2) = TRUE ∧
        Asy_T_Inversion_strain(V3) = TRUE
grd8 : T_Normal_Status = FALSE

```



```

grd9 : Axis_Devi = RAD ∧
        minAngle = 110 ∧
        maxAngle = 180
    then
        act1 : Disease_step6 := pulmonary_embolism
    end

Event T_Wave_Assessment_B ≐
    B for alternate method of T wave assessment

extends T_Wave_Assessment_B

    when
        grd1 : ∀l·l ∈ {I, II, V3, V4, V5, V6} ⇒ T_Wave_State_B(l) = Upright
        grd2 : T_Wave_State_B(aVL) = Inverted_B
        grd3 : ∀l·l ∈ {III, aVL, aVF, V1, V2} ⇒ T_Wave_State_B(l) = Variable
    then
        act1 : T_Normal_Status := TRUE
    end

Event T_Wave_Assessment_B_DI ≐
    abnormal T wave .....in B ...DI(Definite Ischemia)

extends T_Wave_Assessment_B_DI

    when
        grd1 : ∀l·l ∈ LEADS ⇒ T_Wave_State(l) = Inverted
        grd2 : ∀l·l ∈ LEADS ⇒ ST_elevation(l) = TRUE
            ∨
            Q_Normal_Status = FALSE
        grd3 : T_Normal_Status = FALSE
            added in step-8 B
        grd5 : Heart_State = KO
        grd4 : ∃l, k·l ∈ LEADS ∧ k ∈ LEADS ∧
            ((ST_seg_ele(l) ≥ 1000 ∧ ST_seg_ele(k) ≥ 1000) ∨
             (ST_elevation(l) = TRUE ∧ ST_elevation(k) = TRUE))
            ∨
            (Abnormal_Shaped_ST(l) = TRUE ∧ Abnormal_Shaped_ST(k) = TRUE))
            ∧
            l ≠ k
            added in step-8 B
    then
        act1 : Disease_step8 := Definite_ischemia
    end

Event T_Inversion_Likely_Ischemia ≐
    probable Ischemia or Likly ischemia

extends T_Inversion_Likely_Ischemia

    when
        grd1 : ∀l·l ∈ LEADS ⇒ T_Wave_State(l) = Inverted
        grd2 : ∀l·l ∈ LEADS ⇒ ST_elevation(l) = TRUE
            ∨
            Q_Normal_Status = FALSE

```

```

    grd3 :  $\forall l. l \in LEADS \Rightarrow T\_inversion(l) > 5000$ 
           1 mm= 1000
    grd4 :  $\vee$ 
           ( $\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
            ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ ))
            $\vee$ 
           ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
            $\wedge$ 
           ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ ))
            $\Rightarrow l1 \neq k1$ )
grd5 : T_inversion.l.d(V2) = Localized  $\wedge$ 
       T_inversion.l.d(V3) = Localized  $\wedge$ 
       T_inversion.l.d(V4) = Localized  $\wedge$ 
       T_inversion.l.d(V5) = Localized
grd6 : T_inversion.l.d(II) = Localized  $\wedge$ 
       T_inversion.l.d(III) = Localized  $\wedge$ 
       T_inversion.l.d(aVF) = Localized
       b. of Deep inversion  $i$  5mm
grd7 : Heart_State = K0
grd8 : T_Normal_Status = FALSE

    then
        act1 : Disease_step8 := Probable_ischemia
    end

Event T_Inversion_Diffuse_B  $\hat{=}$ 
    Step 8 B for c.

extends T_Inversion_Diffuse_B

    when
        grd1 :  $\vee$ 
               ( $\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
                ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ ))
                $\vee$ 
               ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
                $\wedge$ 
               ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ ))
                $\Rightarrow l1 \neq k1$ )
grd2 :  $\forall l. l \in LEADS \Rightarrow T\_inversion(l) > 5000$ 
grd3 :  $\forall l. l \in LEADS \Rightarrow T\_inversion.l.d(l) = Diffuse$ 
grd4 : Heart_State = K0
grd5 : T_Normal_Status = FALSE

    then
        act1 : Disease_step8.B : $\in$  {Cardiomyopathy, other_nonspecific}
    end

Event Axis_Assessment_QRS_upright_Yes_Age_less_40  $\hat{=}$ 

refines Axis_Assessment_QRS_upright_Yes

    any
        age

    where
        grd1 : QRS_Axis_State(I) = D_Upright  $\wedge$ 
               QRS_Axis_State(aVF) = D_Upright

```

```

    grd2 : age ∈ ℕ ∧ age < 40
  then
    act1 : minAngle := 0
    act2 : maxAngle := 110
  end
Event Axis_Assessment_QRS_upright_Yes_Age_gre_40 ≐
refines Axis_Assessment_QRS_upright_Yes
  any
    age
  where
    grd1 : QRS_Axis_State(I) = D_Upright ∧
           QRS_Axis_State(aVF) = D_Upright
    grd2 : age ∈ ℕ ∧ age > 40
  then
    act1 : minAngle := -30
    act2 : maxAngle := 90
  end
Event Axis_Assessment_QRS_upright_No_QRS_positive ≐
refines Axis_Assessment_QRS_upright_No
  when
    grd1 : ¬(QRS_Axis_State(I) = D_Upright ∧
             QRS_Axis_State(aVF) = D_Upright)
    grd2 : QRS_Axis_State(I) = D_Positive ∧
           QRS_Axis_State(aVF) = D_Positive
    grd3 : Heart_State = KO
  then
    act1 : minAngle := -30
    act2 : maxAngle := -90
    act3 : Axis_Devi := LAD
  end
Event Axis_Assessment_QRS_upright_No_QRS_negative ≐
refines Axis_Assessment_QRS_upright_No
  when
    grd1 : ¬(QRS_Axis_State(I) = D_Upright ∧
             QRS_Axis_State(aVF) = D_Upright)
    grd2 : QRS_Axis_State(I) = D_Negative ∧
           QRS_Axis_State(aVF) = D_Negative
    grd3 : Heart_State = KO
  then
    act1 : minAngle := 110
    act2 : maxAngle := 180
    act3 : Axis_Devi := RAD
  end
Event Misc_Disease_Step9_LAD ≐

```

```

when
  grd1 : Axis_Devi = LAD ∧
        minAngle = -30 ∧
        maxAngle = -90
  grd2 : Heart_State = KO
then
  act1 : Disease_step9 ∈ {LAFB, MSCHD, Some_Form_VT, ED_OC}
end
Event Misc_Disease_Step9_RAD ≐
when
  grd1 : Axis_Devi = RAD ∧
        minAngle = 110 ∧
        maxAngle = 180
  grd2 : Heart_State = KO
then
  act1 : Disease_step9 ∈ {LPFB, Dextrocardia, NV_MSEC}
end
Event R_Q_Assessment_R_Abnormal_V56_axis_deviation ≐
refines R_Q_Assessment_R_Abnormal_V56
when
  grd1 : Q_Wave_State(V5) = TRUE ∧
        Q_Wave_State(V6) = TRUE
  grd2 : Axis_Devi = RAD ∧
        minAngle = 110 ∧
        maxAngle = 180
  grd3 : Heart_State = KO
then
  act1 : Disease_step5 := lateral_MI
end
END

```

An Event-B Specification of Step10.ctx
Generated Date: 25 Nov 2010 @ 03:38:51 PM

CONTEXT Step10.ctx

SETS

Misc_Disease_Codes_Step10

CONSTANTS

Incomplete_RBBB Atrial Septal Defect
Pericarditis
Long_QT
Hypokalemia
Digitalis_toxicity
Electrical_alternans
Electronic_pacing
Hypothermia
Hypercalcemia
NDS10

AXIOMS

axm1 : $Misc_Disease_Codes_Step10 = \{Incomplete_RBBB, Pericarditis, Long_QT, Hypokalemia, Digitalis_toxicity, Electrical_alternans, Electronic_pacing, Hypothermia, Hypercalcemia, NDS10\}$

axm2 : $\neg Incomplete_RBBB = Pericarditis$

axm3 : $\neg Incomplete_RBBB = Long_QT$

axm4 : $\neg Incomplete_RBBB = Hypokalemia$

axm6 : $\neg Incomplete_RBBB = Digitalis_toxicity$

axm7 : $\neg Incomplete_RBBB = Electrical_alternans$

axm8 : $\neg Incomplete_RBBB = Electronic_pacing$

axm9 : $\neg Incomplete_RBBB = Hypothermia$

axm10 : $\neg Incomplete_RBBB = Hypercalcemia$

axm11 : $\neg Incomplete_RBBB = NDS10$

axm12 : $\neg Pericarditis = Long_QT$

axm13 : $\neg Pericarditis = Hypokalemia$

axm15 : $\neg Pericarditis = Digitalis_toxicity$

axm16 : $\neg Pericarditis = Electrical_alternans$

axm17 : $\neg Pericarditis = Electronic_pacing$

axm18 : $\neg Pericarditis = Hypothermia$

axm19 : $\neg Pericarditis = Hypercalcemia$

axm20 : $\neg Pericarditis = NDS10$

axm21 : $\neg Long_QT = Hypokalemia$

axm23 : $\neg Long_QT = Digitalis_toxicity$

axm24 : $\neg Long_QT = Electrical_alternans$

axm25 : $\neg Long_QT = Electronic_pacing$

axm26 : $\neg Long_QT = Hypothermia$

axm27 : \neg Long_QT = Hypercalcemia
axm28 : \neg Long_QT = NDS10
axm30 : \neg Hypokalemia = Digitalis_toxicity
axm31 : \neg Hypokalemia = Electrical_alternans
axm32 : \neg Hypokalemia = Electronic_pacing
axm33 : \neg Hypokalemia = Hypothermia
axm34 : \neg Hypokalemia = Hypercalcemia
axm35 : \neg Hypokalemia = NDS10
axm42 : \neg Digitalis_toxicity = Electrical_alternans
axm43 : \neg Digitalis_toxicity = Electronic_pacing
axm44 : \neg Digitalis_toxicity = Hypothermia
axm45 : \neg Digitalis_toxicity = Hypercalcemia
axm46 : \neg Digitalis_toxicity = NDS10
axm47 : \neg Electrical_alternans = Electronic_pacing
axm48 : \neg Electrical_alternans = Hypothermia
axm49 : \neg Electrical_alternans = Hypercalcemia
axm50 : \neg Electrical_alternans = NDS10
axm51 : \neg Electronic_pacing = Hypothermia
axm52 : \neg Electronic_pacing = Hypercalcemia
axm53 : \neg Electronic_pacing = NDS10
axm54 : \neg Hypothermia = Hypercalcemia
axm55 : \neg Hypothermia = NDS10
axm56 : \neg Hypercalcemia = NDS10

END

An Event-B Specification of Step10_Miscellaneous_conditions
Generated Date: 25 Nov 2010 @ 03:39:47 PM

MACHINE Step10_Miscellaneous_conditions

REFINES Step9_Axis_Assessment_Ref1

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx, Step8_ctx, Step9, Step10_ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
Small_R_QS A small R or QS wave in V1 and V2
Slurred_S_duration Slurred S duration
Delta_Wave Delta Wave
Disease_step3
ST_elevation ST segment elevation (Coved or Saddle-back)
Epsilon_Wave Epsilon Wave or (a terminal notch in the QRS)
ST_seg_ele ST segment for elevation 1mm=0.1mV
Disease_step4
Q_Width Q wave width
Q_Depth Q wave depth
Q_Normal_Status Q wave normal or abnormal
Age_of_Inf Age of Infarct
Disease_step5
Mice_State
R_Depth R wave depth or height (also use in Step 7)
R_Normal_Status R wave normal or abnormal
Q_Wave_State Q wave states for all LEADS
P_Wave_Peak function to estimate the peak of LEADS signal
Disease_step6
PP_Interval
RR_Interval
Diphasic
P_Wave_Broad
S_Depth S wave depth or height

R_S_Ratio R wave and S wave Ratio function
T_Wave_State T wave patterns...
Disease_step8
T_Wave_State_B B for alternative method of T wave assessment
T_Normal_Status T wave normal or abnormal
Abnormal_Shaped_ST
Asy_T_Inversion_strain Asymmetric T wave Inversion strain pattern
T_inversion Deep T wave inversion
T_inversion_l_d T inversion Localized and Diffuse
Disease_step8_B
QRS_Axis_State QRS Axis Direction
minAngle min. value of angle of Axis in degree
maxAngle max. value of angle of Axis in degree
Axis_Devi Axis Deviation in LEADS...
Disease_step9
Disease_step10
MC_Step10_Test_Needed Miscellaneous Conditions test in Step 10
ST_depression

INVARIANTS

inv1: $Disease_step10 \in Misc_Disease_Codes_Step10$
inv2: $MC_Step10_Test_Needed \in BOOL$
inv3: $Sinus = Yes \wedge Disease_step10 \in \{Incomplete_RBBB, Pericarditis, Long_QT, Hypokalemia, Digitalis_toxicity, Electrical_alternans, Electronic_pacing, Hypothermia, Hypercalcemia\} \Rightarrow Heart_State = KO$
inv4: $Sinus = Yes \wedge Disease_step9 = Dextrocardia \Rightarrow Heart_State = KO$

EVENTS

Initialisation

extended

begin

act1: $RR_Int_equidistant : \in LEADS \rightarrow BOOL$
act2: $PP_Int_equidistant : \in LEADS \rightarrow BOOL$
act3: $P_Positive : \in LEADS \rightarrow BOOL$
act4: $Sinus := No$
act5: $PP_Interval : \in LEADS \rightarrow \mathbb{N}$
act6: $RR_Interval : \in LEADS \rightarrow \mathbb{N}$
act7: $Heart_Rate : \in 1 .. 300$
act8: $Heart_State := KO$
act9: $PR_Int := 120$
act10: $Disease_step2 := NDS2$
act11: $QRS_Int := 50$
act12: $Notched_R : \in LEADS \rightarrow BOOL$
act13: $Small_R_QS : \in LEADS \rightarrow BOOL$
act14: $Slurred_S_duration : \in LEADS \rightarrow \mathbb{N}_1$
act15: $M_Shape_Complex : \in LEADS \rightarrow BOOL$
act16: $Slurred_S : \in LEADS \rightarrow BOOL$


```

act17 : ST_elevation :∈ LEADS → BOOL
act18 : Epsilon_Wave :∈ LEADS → BOOL
act19 : Delta_Wave := 0
act20 : Disease_step3 := NDS3
act21 : ST_seg_ele :∈ LEADS → ℕ
act22 : Disease_step4 := NDS4
act57 : ST_depression :∈ LEADS → ℕ
act23 : Q_Width :∈ LEADS → ℕ
act24 : Q_Depth :∈ LEADS → ℕ
act25 : Q_Normal_Status := FALSE
act26 : Mice_State := NMS
act27 : R_Depth :∈ LEADS → ℕ
act28 : R_Normal_Status := FALSE
act29 : Q_Wave_State :∈ LEADS → BOOL
act30 : Age_of_Inf :∈ Age_of_Infarct
act31 : Disease_step5 := NDS5
act32 : Diphasic :∈ LEADS → BOOL
act33 : P_Wave_Broad :∈ LEADS → ℕ
act34 : P_Wave_Peak :∈ LEADS → ℕ
act35 : Disease_step6 := NDS6
act36 : S_Depth :∈ LEADS → ℕ
act37 : R_S_Ratio :∈ LEADS → ℕ
act38 : T_Wave_State :∈ LEADS → T_State
act39 : Disease_step8 := NDS8
act40 : Abnormal_Shaped_ST :∈ LEADS → BOOL
act41 : Asy_T_Inversion_strain :∈ LEADS → BOOL
act43 : T_inversion_l_d :∈ LEADS → T_State_l_d
act42 : T_inversion :∈ LEADS → ℕ
act44 : Disease_step8_B := NDS8B
act45 : T_Wave_State_B :∈ LEADS → T_State_B
act46 : T_Normal_Status := FALSE
act47 : QRS_Axis_State :∈ LEADS → QRS_directions
act48 : minAngle := 0
act49 : maxAngle := 0
act50 : Axis_Devi := ND
act51 : Disease_step9 := NDS9
act52 : Disease_step10 := NDS10
act53 : MC_Step10_Test_Needed := FALSE

```

end

Event *Rhythm_test_TRUE* $\hat{=}$
Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

any

rate

where

```

grd1 : (∃!l · l ∈ {II, V1, V2} ∧ PP_Int.equidistant(l) = TRUE ∧
RR_Int.equidistant(l) = TRUE ∧
RR.Interval(l) = PP.Interval(l))
∧
P_Positive(II) = TRUE

```

```

grd4 : rate  $\in$  60..100
      60..100 is the range of normal heart rate
grd5 : PR_Int  $\leq$  200
      Heart is Normal if PR  $\leq$  200 QRS_Int  $<$  120
      Heart is Normal if QRS  $<$  120
grd7 : Disease_step2 = NDS2
grd8 : Disease_step3 = NDS3
grd9 : Disease_step4 = NDS4
grd10 : Disease_step5 = NDS5
grd11 : Disease_step6 = NDS6
grd12 : Disease_step8 = NDS8
grd13 : Disease_step8_B = NDS8B
grd14 : Disease_step9 = NDS9
grd15 : Disease_step10 = NDS10

then
  act1 : Sinus := Yes
  act2 : Heart_Rate := rate
  act3 : Heart_State := OK
end

Event Rhythm_test_FALSE  $\hat{=}$ 
  Abnormal Rhythm with Rate

extends Rhythm_test_FALSE

any
  rate

where
  grd1 : ( $\forall l. l \in \{II, V1, V2\} \Rightarrow$  PP_Int_equidistant(1) = FALSE  $\vee$ 
        RR_Int_equidistant(1) = FALSE  $\vee$ 
        RR_Interval(1)  $\neq$  PP_Interval(1))
         $\vee$ 
        P_Positive(II) = FALSE
  grd2 : rate  $\in$  1..300

then
  act1 : Sinus := No
  act2 : Heart_Rate := rate
  act3 : Heart_State := KO
end

Event Rhythm_test_TRUE_Rate  $\hat{=}$ 
  Sinus Rhythm with abnormal Rate

extends Rhythm_test_TRUE_Rate

any
  rate

where
  grd1 : ( $\exists l. l \in \{II, V1, V2\} \wedge$  PP_Int_equidistant(1) = TRUE  $\wedge$ 
        RR_Int_equidistant(1) = TRUE  $\wedge$ 
        RR_Interval(1) = PP_Interval(1))
         $\wedge$ 
        P_Positive(II) = TRUE

```

```

    grd5 : rate ∈ 1..300 \ 60..100
           60..100 is the range of normal heart rate, so rest of no. is abnormal
    grd6 : Disease_step3 = WPW_Syndrome ∨ Disease_step3 = Brugada_Syndrome ∨
           Disease_step3 = RV_Dysplasia ∨ Disease_step3 = IVCD

  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end

Event PR_Test ≐
  PR Interval Test

extends PR_Test

  any
    pr
  where
    grd1 : pr ∈ 120..220
           time interval in (ms.)
    grd2 : pr > 200
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
  then
    act1 : PR_Int := pr
    act2 : Disease_step2 := First_degree_AV_Block
  end

Event QRS_Test_LBBB ≐
  QRS Complex Interval Test

extends QRS_Test_LBBB

  any
    qrs
  where
    grd1 : qrs ∈ 50..150
    grd2 : qrs ≥ 120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : Notched_R(I) = TRUE ∧
           Notched_R(V5) = TRUE ∧
           Notched_R(V6) = TRUE
           Right Bundle Branch Block (RBBB)
    grd6 : Small_R_QS(V1) = TRUE ∧
           Small_R_QS(V2) = TRUE
    grd7 : Q_Wave_State(V1) = TRUE ∧
           Q_Wave_State(V2) = TRUE ∧
           Q_Wave_State(V3) = TRUE ∧
           Q_Wave_State(V4) = TRUE
           from step 5
    grd8 : R_Normal_Status = FALSE
           from step 5

```

```

    grd9 : Axis_Devi = LAD ∧
           minAngle = -30 ∧
           maxAngle = -90
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := LBBB
  end
Event QRS_Test_RBBB ≐
  Right Bundle Branch Block (RBBB)
extends QRS_Test_RBBB
  any
    qrs
  where
    grd1 : qrs ∈ 50 .. 150
    grd2 : qrs ≥ 120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : M_Shape_Complex(V1) = TRUE ∧
           M_Shape_Complex(V2) = TRUE
    grd7 : Slurred_S(I) = TRUE ∧
           Slurred_S(V5) = TRUE ∧
           Slurred_S(V6) = TRUE
    grd8 : Slurred_S.duration(I) > 40 ∧
           Slurred_S.duration(V5) > 40 ∧
           Slurred_S.duration(V6) > 40
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := RBBB
  end
Event QRS_Test_Atypical_RLBBB-WPW_Syndrome ≐
  QRS Test for Atypical LBBB RBBB
extends QRS_Test_Atypical_RLBBB-WPW_Syndrome
  any
    sympt
    d_wave
    exmi
  where
    grd1 : QRS_Int ≥ 110
    grd2 : sympt = A_RBBB ∨ sympt = A_LBBB
    grd3 : d_wave ∈ ℕ
    grd4 : (d_wave + PR_Int) ≤ 120
           Delta_Wave + PR ≤ 120 Heart_State = KO
    grd5 : Disease_step4 = Acute_inferior_MI
    grd6 : Disease_step4 = Acute_inferior_MI
    grd7 : exmi ∈ Mice_State5 ∧ exmi = Exclude_Mimics_MI
  then
    act2 : Delta_Wave := d_wave
    act3 : Disease_step3 := WPW_Syndrome

```

```

end

Event QRS_Test_Atypical_RBBB_Brugada_Syndrome  $\hat{=}$ 
  Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends QRS_Test_Atypical_RBBB_Brugada_Syndrome

any
  sympt
  dis

where
  grd1 : sympt = A_RBBB
  grd2 : Heart_State = KO
  grd3 : QRS_Int  $\geq$  110
  grd4 : Slurred_S(V5) = FALSE  $\wedge$ 
        Slurred_S(V6) = FALSE
  grd5 : dis  $\in$  Disease_Codes_Step3 \ {WPW_Syndrome, NDS3}
  grd6 : ST_elevation(V1) = TRUE  $\wedge$ 
        ST_elevation(V2) = TRUE
  grd7 : Sinus = Yes

then
  act1 : Disease_step3 := Brugada_Syndrome

end

Event QRS_Test_Atypical_RBBB_RV_Dysplasia  $\hat{=}$ 
  Right Ventricular Dysplasia

extends QRS_Test_Atypical_RBBB_RV_Dysplasia

any
  sympt
  dis

where
  grd1 : sympt = A_RBBB
  grd2 : Heart_State = KO
  grd3 : QRS_Int  $\geq$  110
  grd4 : dis  $\in$  Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, NDS3}
  grd5 : Epsilon_Wave(V1) = TRUE  $\wedge$ 
        Epsilon_Wave(V3) = TRUE

then
  act1 : Disease_step3 := RV_Dysplasia

end

Event QRS_Test_Atypical_RBBB_IVCD  $\hat{=}$ 
  IVCD diagnosis

extends QRS_Test_Atypical_RBBB_IVCD

any
  dis

where
  grd1 : QRS_Int  $\geq$  110
  grd2 : dis  $\in$  Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, NDS3}
  grd3 : Heart_State = KO

```

```

then
  act1 : Disease_step3 := IVCD
end

Event ST_seg_elevation_YES  $\hat{=}$ 
  ST segment elevation...

extends ST_seg_elevation_YES

when
  grd1 : Heart_State = KO
  grd2 : Sinus = Yes
  grd3 :  $\vee$ 
  (( $\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
  (ST_elevation(l1) = TRUE  $\wedge$  ST_elevation(k1) = TRUE)
   $\wedge$ 
  (ST_seg_ele(l1)  $\geq$  1000  $\wedge$  ST_seg_ele(k1)  $\geq$  1000)
   $\wedge$  l1  $\neq$  k1
   $\wedge$ 
  (
  (l1 = V1  $\wedge$  k1 = V2)  $\vee$ 
  (l1 = V2  $\wedge$  k1 = V3)  $\vee$ 
  (l1 = V3  $\wedge$  k1 = V4)  $\vee$ 
  (l1 = V4  $\wedge$  k1 = V5)  $\vee$ 
  (l1 = V5  $\wedge$  k1 = V6)
  )
  ))
grd4 : Disease_step4  $\in$  {Acute_inferior_MI, Acute_anterior_MI}
then
  act1 : Disease_step4 := STEMI
end

Event ST_seg_elevation_NOTCKMB_Yes  $\hat{=}$ 
  Troponin or CK-MB positive YES

extends ST_seg_elevation_NOTCKMB_Yes

when
  grd1 : Heart_State = KO
  grd2 : Sinus = Yes
  grd3 :  $\vee$ 
  ( $\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$ 
  (ST_elevation(l1) = FALSE  $\wedge$  ST_seg_ele(l1) < 1000))
grd4 :  $\exists l, k \cdot l \in \text{LEADS} \wedge k \in \text{LEADS} \wedge$ 
  (ST_depression(l)  $\geq$  1000  $\wedge$  ST_depression(k)  $\geq$  1000)
   $\wedge$  l  $\neq$  k
grd5 : Disease_step4  $\in$  {Troponin, CK_MB}
then
  act1 : Disease_step4 := Non_STEMI
end

Event ST_seg_elevation_NO_TCKMB_No  $\hat{=}$ 
  Troponin or CK-MB positive No

extends ST_seg_elevation_NO_TCKMB_No

```

```

when
  grd1 : Heart_State = KO
  grd2 : Sinus = Yes
  grd3 :
    ∨
    (∀l1·l1 ∈ {II, III, aVF} ⇒
    (ST_elevation(l1) = FALSE ∧ ST_seg_ele(l1) < 1000))
grd4 : ∃l, k·l ∈ LEADS ∧ k ∈ LEADS ∧
  (ST_depression(l) ≥ 1000 ∧ ST_depression(k) ≥ 1000)
  ∧ l ≠ k
grd5 : Disease_step4 ∉ {Troponin, CK_MB}
grd6 : ∀l·l ∈ LEADS ⇒ T_inversion(l) < 5000
grd7 : T_Normal_Status = FALSE
then
  act1 : Disease_step4 := Ischemia
end

Event Q_Assessment_Normal ≐
  Q wave assessment normal

extends Q_Assessment_Normal

when
  grd1 : Q_Width(II) < 40 ∧ Q_Depth(II) ≤ 3000 ∧
    Q_Width(aVF) < 40 ∧ Q_Depth(aVF) ≤ 3000 ∧
    Q_Width(aVL) < 40
    1000 micrometer = 1 millimeter
  grd2 : Q_Width(III) ≤ 40 ∧ Q_Depth(III) ≤ 7000 ∧ Q_Depth(aVL) ≤ 7000
  grd3 : Q_Depth(I) < 40 ∧ Q_Depth(I) ≤ 1500
then
  act1 : Q_Normal_Status := TRUE
end

Event Q_Assessment_Abnormal_AMI ≐
  Q wave assessment abnormal for anterolateral MI (AMI)

extends Q_Assessment_Abnormal_AMI

when
  grd1 : Heart_State = KO
  grd2 : Sinus = Yes
  grd3 :
    ∨
    ((∃l1, k1·l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
    (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
    ∧
    (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
    ∧ l1 ≠ k1
    ∧
    (
    (l1 = V1 ∧ k1 = V2) ∨
    (l1 = V2 ∧ k1 = V3) ∨
    (l1 = V3 ∧ k1 = V4) ∨
    (l1 = V4 ∧ k1 = V5) ∨
    (l1 = V5 ∧ k1 = V6)
    )
    ))

```

```

grd4 : Q_Width(V5) ≥ 40 ∧ Q_Depth(V5) > 3000 ∧
      Q_Width(V6) ≥ 40 ∧ Q_Depth(V6) > 3000
grd5 : Q_Width(aVL) ≥ 40 ∧ Q_Depth(aVL) > 7000
grd6 : Q_Depth(I) ≥ 40 ∧ Q_Depth(I) > 1500
grd7 : Q_Normal_Status = FALSE
      then
          act1 : Disease_step4 := Acute_anterior_MI
      end

Event Q_Assessment_Abnormal_IMI ≐
  Q wave assessment abnormal for inferior MI (IMI)

extends Q_Assessment_Abnormal_IMI

when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :
        ∨
        ((∃ l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
          (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
          ∧
          (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
          ∧ l1 ≠ k1
          ∧
          (
            (l1 = V1 ∧ k1 = V2) ∨
            (l1 = V2 ∧ k1 = V3) ∨
            (l1 = V3 ∧ k1 = V4) ∨
            (l1 = V4 ∧ k1 = V5) ∨
            (l1 = V5 ∧ k1 = V6)
          )
        ))
grd4 : Q_Width(II) ≥ 40 ∧ Q_Depth(II) > 3000 ∧
      Q_Width(III) > 40 ∧ Q_Depth(III) > 7000 ∧
      Q_Width(aVF) ≥ 40 ∧ Q_Depth(aVF) > 3000
grd5 : Q_Normal_Status = FALSE
      then
          act1 : Disease_step4 := Acute_inferior_MI
      end

Event Determine_Age_of_Infarct ≐

extends Determine_Age_of_Infarct

when
    grd1 : Disease_step4 = Acute_inferior_MI
          ∨
          Disease_step5 ∈ {anterior_MI, LVH, emphysema}
          ∨
          Mice_State = Exclude_Mimics_MI
          ∨
          Disease_step2 = LBBB

      then
          act1 : Age_of_Inf :∈ {recent, old, indeterminate}
      end
end

```



```

Event Exclude_Mimics  $\hat{=}$ 
extends Exclude_Mimics
  any
    exmi
  where
    grd1 : Disease_step4 = Acute_inferior_MI
    grd2 : exmi  $\in$  Mice_State5  $\wedge$  exmi = Exclude_Mimics_MI
  then
    act1 : Disease_step5 := Hypertrophic_cardiomyopathy
    act2 : Mice_State := borderline_Qs
  end

Event R_Assessment_Normal  $\hat{=}$ 
  Q wave assessment normal
extends R_Assessment_Normal
  any
    age
  where
    grd1 : R.Depth(V1)  $\geq$  0  $\wedge$  R.Depth(V1)  $\leq$  6000  $\wedge$  age > 30
      1000 micrometer = 1 millimeter
    grd2 : R.Depth(V2) > 200  $\wedge$  R.Depth(V2)  $\leq$  12000
    grd3 : R.Depth(V2)  $\geq$  1000  $\wedge$  R.Depth(V2)  $\leq$  24000
  then
    act1 : R.Normal_Status := TRUE
  end

Event R_Assessment_Abnormal  $\hat{=}$ 
extends R_Assessment_Abnormal
  when
    grd1 : R.Normal_Status = FALSE
  then
    act1 : Mice_State  $\in$  {late_transition, normal_variant}
  end

Event R_Q_Assessment_R_Abnormal_V1234  $\hat{=}$ 
  R wave abnormal , pathologic Q waves consider in V1-V4
extends R_Q_Assessment_R_Abnormal_V1234
  when
    grd1 : R.Normal_Status = FALSE
    grd2 : Q.Wave_State(V1) = TRUE  $\wedge$ 
      Q.Wave_State(V2) = TRUE  $\wedge$ 
      Q.Wave_State(V3) = TRUE  $\wedge$ 
      Q.Wave_State(V4) = TRUE
    grd3 : Heart_State = KO
  then
    act1 : Disease_step5  $\in$  {anterior_MI, LVH, emphysema}

```

```

        act2 : Mice_State := Exclude_Mimics_MI
    end
Event R_Q_Assessment_R_Abnormal_V56  $\hat{=}$ 
    R wave abnormal , pathologic Q waves consider in V5-V6
extends R_Q_Assessment_R_Abnormal_V56
    when
        grd1 : Q_Wave_State(V5) = TRUE  $\wedge$ 
            Q_Wave_State(V6) = TRUE
        grd2 : Heart_State = KO
    then
        act1 : Disease_step5 := Hypertrophic_cardiomyopathy
    end
Event P_Wave_assessment_Peaked_Broad_No  $\hat{=}$ 
extends P_Wave_assessment_Peaked_Broad_No
    when
        grd1 : (P_Wave_Peak(II) < 3000  $\wedge$ 
            P_Wave_Peak(V1) < 3000)
             $\vee$ 
            (P_Wave_Broad(II) < 110  $\wedge$  P_Wave_Broad(V1) < 110)  $\vee$ 
            Diphasic(II) = FALSE  $\vee$ 
            Diphasic(V1) = FALSE
    then
        act1 : Disease_step6 := NDS6
    end
Event P_Wave_assessment_Peaked_Yes  $\hat{=}$ 
extends P_Wave_assessment_Peaked_Yes
    when
        grd1 : P_Wave_Peak(II)  $\geq$  3000
        grd2 : P_Wave_Peak(V1)  $\geq$  3000
        grd3 : Heart_State = KO
    then
        act1 : Disease_step6 := RAE
    end
Event P_Wave_assessment_Peaked_Yes_Check_RAE  $\hat{=}$ 
extends P_Wave_assessment_Peaked_Yes_Check_RAE
    when
        grd1 : P_Wave_Peak(II)  $\geq$  3000
        grd2 : P_Wave_Peak(V1)  $\geq$  3000
        grd3 : Disease_step6 = RAE
        grd4 : Heart_State = KO
    then
        act1 : Disease_step6 := RV_strain
    end

```

Event *P_Wave_assessment_Broad_Yes* $\hat{=}$

extends *P_Wave_assessment_Broad_Yes*

when

grd1 : (P_Wave_Broad(II) \geq 110 \wedge P_Wave_Broad(V1) \geq 110) \vee
Diphasic(II) = TRUE \vee
Diphasic(V1) = TRUE
grd2 : Heart_State = KO

then

act1 : Disease_step6 := LAE

end

Event *P_Wave_assessment_Broad_Yes_Check_LAE* $\hat{=}$

extends *P_Wave_assessment_Broad_Yes_Check_LAE*

when

grd1 : (P_Wave_Broad(II) \geq 110 \wedge P_Wave_Broad(V1) \geq 110) \vee
Diphasic(II) = TRUE \vee
Diphasic(V1) = TRUE
grd2 : Disease_step6 = LAE
grd3 : Heart_State = KO

then

act1 : Disease_step6 \in {mitral_stenosis, mitral_regurgitation,
LV_failure, dilated_cardiomyopathy}

end

Event *LVH_Assessment* $\hat{=}$

LVH Assessment

extends *LVH_Assessment*

any

LVH_specificity specificity in percentage
sensitivity sensitivity in percentage
sex

where

grd1 : (P_Wave_Broad(II) \geq 110 \wedge P_Wave_Broad(V1) \geq 110) \vee
Diphasic(II) = TRUE \vee
Diphasic(V1) = TRUE

grd2 : Disease_step6 = LAE

grd5 : sex \in {0, 1}
o for men and 1 for women

grd3 : ((S_Depth(V1) + R_Depth(V5)) > 35000
 \vee

(S_Depth(V1) + R_Depth(V6)) > 35000)

1mm = 1000 micrometer..... 1 assessment

grd4 : ((R_Depth(aVL) + S_Depth(V1) \geq 24000) \wedge sex = 0)

\vee
((R_Depth(aVL) + S_Depth(V1) \geq 18000) \wedge sex = 1)

2 assessment

grd6 : LVH_specificity = 90

\wedge
sensitivity < 40

1 and 2 assessment

```

    grd7 : Disease_step6 = LAE  $\Rightarrow$  LVH_specificity < 98
           3 assessment
    grd8 :      ( $\forall t \cdot t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$ 
                 $\vee$ 
                 $Q\_Normal\_Status = FALSE$ )
           A or B : from step 8 development
    grd9 :       $\vee$ 
           ( $\forall l1, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
           ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
            $\vee$ 
           ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
            $\wedge$ 
           ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ ))
            $\Rightarrow l1 \neq k1$ )
    grd10 : Asy_T_Inversion_strain(V5) = TRUE  $\wedge$ 
            Asy_T_Inversion_strain(V6) = TRUE  $\wedge$ 
            Asy_T_Inversion_strain(V4) = TRUE
    grd11 : Heart_State = KO
    grd12 : T_Normal_Status = FALSE
    grd13 : Axis_Devi = LAD  $\wedge$ 
            minAngle = -30  $\wedge$ 
            maxAngle = -90

    then
        act1 : Disease_step6 := LVH_cause
    end

Event RVH_Assessment  $\hat{=}$ 
    RVH_Assessment

extends RVH_Assessment

    any
        age    age od men or women
        aixs   axis for deviation

    where
        grd1 : P_Wave_Peak(II)  $\geq$  3000
        grd2 : P_Wave_Peak(V1)  $\geq$  3000
        grd3 : Disease_step6 = RAE
        grd4 : R_Depth(V1)  $\geq$  7000  $\wedge$  age > 30
                1 assessment
        grd5 : S_Depth(V5)  $\geq$  7000  $\vee$ 
                S_Depth(V6)  $\geq$  7000
                2 assessment
        grd6 : R_S_Ratio(V1)  $\geq$  100
                R_S Ratio is multiply by 100 to remove the real no. constants... 3 assessment
        grd7 : R_S_Ratio(V5)  $\leq$  100
                 $\vee$ 
                R_S_Ratio(V6)  $\leq$  100
                4 assessment
        grd8 : aixs  $\in$  0 .. 360  $\wedge$  aixs  $\geq$  110
                5 assessment
        grd9 : Disease_step2  $\notin$  {LBBB, RBBB}
        grd10 : QRS_Int < 120

```

```

grd11 :      ( $\forall t.t \in LEADS \Rightarrow ST\_elevation(t) = TRUE$ 
               $\vee$ 
               $Q\_Normal\_Status = FALSE$ ))

AorB : fromstep8development
       $\vee$ 
      ( $\forall l1, k1.l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
      ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
       $\vee$ 
      ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
       $\wedge$ 
      ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ ))
       $\Rightarrow l1 \neq k1$ ))

grd12 grd13 : Asy_T_Inversion_strain(V1) = TRUE  $\wedge$ 
              Asy_T_Inversion_strain(V2) = TRUE  $\wedge$ 
              Asy_T_Inversion_strain(V3) = TRUE

grd14 : Heart_State = KO
grd15 : T_Normal_Status = FALSE
grd16 : Axis_Devi = RAD  $\wedge$ 
              minAngle = 110  $\wedge$ 
              maxAngle = 180

then
  act1 : Disease_step6 := RVH
end

Event T_Wave_Assessment_Peaked_V123456  $\hat{=}$ 
  T_Wave_Assessment

refines T_Wave_Assessment_Peaked_V123456

when
  grd1 :  $\forall l.l \in \{V1, V2, V3, V4, V5, V6\} \Rightarrow T\_Wave\_State(l) = Peaked$ 
  grd2 : MC_Step10_Test_Needed = TRUE
  grd3 : Heart_State = KO

then
  act1 : Disease_step8 := Hyperkalemia
end

Event T_Wave_Assessment_Peaked_V12  $\hat{=}$ 

extends T_Wave_Assessment_Peaked_V12

when
  grd1 : R_Normal_Status = FALSE
  grd2 : T_Wave_State(V1) = Peaked  $\wedge$ 
              T_Wave_State(V2) = Peaked
  grd3 :       $\vee$ 
              ( $\forall l1, k1.l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
              ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
               $\vee$ 
              ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
               $\wedge$ 
              ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ ))
               $\Rightarrow l1 \neq k1$ ))

grd4 :  $\forall l.l \in LEADS \Rightarrow T\_inversion(l) < 5000$ 
step 8 B

```

```

grd5 : T_Normal_Status = FALSE
grd6 :
    ∨
    (Axis_Devi = RAD ∧
     minAngle = 110 ∧
     maxAngle = 180)
  then
    act1 : Mice_State := normal_variant
  end

Event T_Wave_Assessment_Peaked_V12_MI ≐
  posterior MI using T wave assessment in LEADS V1 and V2

extends T_Wave_Assessment_Peaked_V12_MI

when
  grd1 : T_Wave_State(V1) = Peaked ∧
        T_Wave_State(V2) = Peaked
  grd6 : Heart_State = KO
  grd2 :
    ∨
    (∀l1, k1. l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
     ((ST_elevation(l1) = FALSE ∨ ST_elevation(k1) = FALSE)
     ∨
     ((ST_seg_ele(l1) < 1000 ∨ ST_seg_ele(k1) < 1000)
     ∧
     (Abnormal_Shaped_ST(l1) = FALSE ∨ Abnormal_Shaped_ST(k1) = FALSE)))
     ⇒ l1 ≠ k1))
grd3 : ∀l. l ∈ LEADS ⇒ T_inversion(l) > 5000
grd4 : T_inversion.l.d(V2) = Localized ∧
      T_inversion.l.d(V3) = Localized ∧
      T_inversion.l.d(V4) = Localized ∧
      T_inversion.l.d(V5) = Localized
grd5 : T_inversion.l.d(II) = Localized ∧
      T_inversion.l.d(III) = Localized ∧
      T_inversion.l.d(aVF) = Localized
grd7 : T_Normal_Status = FALSE
  then
    act1 : Disease_step8 := posterior_MI
  end

Event T_Wave_Assessment_Flat ≐

extends T_Wave_Assessment_Flat

when
  grd1 : ∀l. l ∈ LEADS ⇒ T_Wave_State(l) = Flat
  grd4 : Heart_State = KO
  grd2 :
    ∨
    (∀l1, k1. l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
     ((ST_elevation(l1) = FALSE ∨ ST_elevation(k1) = FALSE)
     ∨
     ((ST_seg_ele(l1) < 1000 ∨ ST_seg_ele(k1) < 1000)
     ∧
     (Abnormal_Shaped_ST(l1) = FALSE ∨ Abnormal_Shaped_ST(k1) = FALSE)))
     ⇒ l1 ≠ k1))
step 8 B

```

```

grd3 :  $\forall l \cdot l \in \text{LEADS} \Rightarrow \text{T\_inversion}(l) < 5000$ 
grd5 :  $\text{T\_Normal\_Status} = \text{FALSE}$ 
  then
    act1 :  $\text{Disease\_step8} := \text{Nonspecific\_ST\_T\_changes}$ 
    act2 :  $\text{Disease\_step8\_B} \in \{\text{Cardiomyopathy}, \text{Electrolyte\_depletion}, \text{Alcohol}, \text{Myocarditis}, \text{Other}\}$ 
  end
Event  $T\_Wave\_Assessment\_Inverted\_Yes \hat{=}$ 
extends  $T\_Wave\_Assessment\_Inverted\_Yes$ 
  when
    grd1 :  $\forall l \cdot l \in \text{LEADS} \Rightarrow \text{T\_Wave\_State}(l) = \text{Inverted}$ 
    grd2 :  $\forall l \cdot l \in \text{LEADS} \Rightarrow \text{ST\_elevation}(l) = \text{TRUE}$ 
            $\vee$ 
            $Q\_Normal\_Status = \text{FALSE}$ 
    grd3 :  $\text{Heart\_State} = \text{KO}$ 
  then
    act1 :  $\text{Disease\_step8} \in \{\text{Definite\_ischemia}, \text{Probable\_ischemia}, \text{Digitalis\_effect}\}$ 
  end
Event  $T\_Wave\_Assessment\_Inverted\_No \hat{=}$ 
extends  $T\_Wave\_Assessment\_Inverted\_No$ 
  when
    grd1 :  $\forall l \cdot l \in \text{LEADS} \Rightarrow \text{T\_Wave\_State}(l) = \text{Inverted}$ 
    grd2 :  $\forall l \cdot l \in \text{LEADS} \Rightarrow \text{ST\_elevation}(l) = \text{FALSE}$ 
            $\vee$ 
            $Q\_Normal\_Status = \text{TRUE}$ 
    grd3 :  $\text{Heart\_State} = \text{KO}$ 
  then
    act1 :  $\text{Disease\_step8} := \text{Nonspecific}$ 
  end
Event  $T\_Wave\_Assessment\_Inverted\_Yes\_PM \hat{=}$ 
  PM - pulmonary embolism this disease is already defined in previous development.
refines  $T\_Wave\_Assessment\_Inverted\_Yes\_PM$ 
  when
    grd1 :  $P\_Wave\_Peak(II) \geq 3000$ 
    grd2 :  $P\_Wave\_Peak(V1) \geq 3000$ 
    grd3 :  $\text{Disease\_step6} = \text{RAE}$ 
    grd4 :  $(\forall t \cdot t \in \text{LEADS} \Rightarrow \text{ST\_elevation}(t) = \text{TRUE})$ 
            $\vee$ 
            $(Q\_Normal\_Status = \text{FALSE})$ 
A : step8
   $\neg(\exists l, k \cdot l \in \text{LEADS} \wedge k \in \text{LEADS} \wedge$ 
   $((\text{ST\_seg\_ele}(l) \geq 1000 \wedge \text{ST\_seg\_ele}(k) \geq 1000) \vee$ 
   $(\text{ST\_elevation}(l) = \text{TRUE} \wedge \text{ST\_elevation}(k) = \text{TRUE}))$ 
   $\vee$ 
   $(\text{Abnormal\_Shaped\_ST}(l) = \text{TRUE} \wedge \text{Abnormal\_Shaped\_ST}(k) = \text{TRUE}))$ 
   $\Rightarrow$ 
   $l \neq k))$ 

```

```

grd6 : Asy_T_Inversion_strain(V1) = TRUE ∧
      Asy_T_Inversion_strain(V2) = TRUE ∧
      Asy_T_Inversion_strain(V3) = TRUE
grd7 : Axis_Devi = RAD ∧
      minAngle = 110 ∧
      maxAngle = 180
grd8 : MC_Step10_Test_Needed = TRUE
grd9 : Heart_State = KO
      then
        act1 : Disease_step6 := pulmonary_embolism
      end

Event T_Wave_Assessment_B ≐
  B for alternate method of T wave assessment

extends T_Wave_Assessment_B

when
  grd1 : ∀l·l ∈ {I, II, V3, V4, V5, V6} ⇒ T_Wave_State_B(l) = Upright
  grd2 : T_Wave_State_B(aVL) = Inverted_B
  grd3 : ∀l·l ∈ {III, aVL, aVF, V1, V2} ⇒ T_Wave_State_B(l) = Variable
then
  act1 : T_Normal_Status := TRUE
end

Event T_Wave_Assessment_B_DI ≐
  abnormal T wave .....in B ...DI(Definite Ischemia)

extends T_Wave_Assessment_B_DI

when
  grd1 : ∀l·l ∈ LEADS ⇒ T_Wave_State(l) = Inverted
  grd2 : ∀l·l ∈ LEADS ⇒ ST_elevation(l) = TRUE
        ∨
        Q_Normal_Status = FALSE
  grd3 : T_Normal_Status = FALSE
        added in step-8 B
  grd5 : Heart_State = KO
  grd4 : ∃l, k·l ∈ LEADS ∧ k ∈ LEADS ∧
        ((ST_seg_ele(l) ≥ 1000 ∧ ST_seg_ele(k) ≥ 1000) ∨
         (ST_elevation(l) = TRUE ∧ ST_elevation(k) = TRUE))
        ∨
        (Abnormal_Shaped_ST(l) = TRUE ∧ Abnormal_Shaped_ST(k) = TRUE))
        ∧
        l ≠ k
        added in step-8 B
then
  act1 : Disease_step8 := Definite_ischemia
end

Event T_Inversion_Likely_Ischemia ≐
  probable Ischemia or Likly ischemia

extends T_Inversion_Likely_Ischemia

when

```



```

    grd1 :  $\forall l. l \in \text{LEADS} \Rightarrow \text{T\_Wave\_State}(l) = \text{Inverted}$ 
    grd2 :  $\forall l. l \in \text{LEADS} \Rightarrow \text{ST\_elevation}(l) = \text{TRUE}$ 
            $\vee$ 
            $\text{Q\_Normal\_Status} = \text{FALSE}$ 
    grd3 :  $\forall l. l \in \text{LEADS} \Rightarrow \text{T\_inversion}(l) > 5000$ 
            $1 \text{ mm} = 1000$ 
    grd4 :            $\vee$ 
           ( $\forall l, k1. l1 \in \text{LEADS} \wedge k1 \in \text{LEADS} \wedge$ 
            ( $\text{ST\_elevation}(l1) = \text{FALSE} \vee \text{ST\_elevation}(k1) = \text{FALSE}$ )
             $\vee$ 
            ( $\text{ST\_seg\_ele}(l1) < 1000 \vee \text{ST\_seg\_ele}(k1) < 1000$ )
             $\wedge$ 
            ( $\text{Abnormal\_Shaped\_ST}(l1) = \text{FALSE} \vee \text{Abnormal\_Shaped\_ST}(k1) = \text{FALSE}$ ))
             $\Rightarrow l1 \neq k1$ )
    grd5 :  $\text{T\_inversion.l.d}(V2) = \text{Localized} \wedge$ 
            $\text{T\_inversion.l.d}(V3) = \text{Localized} \wedge$ 
            $\text{T\_inversion.l.d}(V4) = \text{Localized} \wedge$ 
            $\text{T\_inversion.l.d}(V5) = \text{Localized}$ 
    grd6 :  $\text{T\_inversion.l.d}(II) = \text{Localized} \wedge$ 
            $\text{T\_inversion.l.d}(III) = \text{Localized} \wedge$ 
            $\text{T\_inversion.l.d}(aVF) = \text{Localized}$ 
    b. of Deep inversion  $i$  5mm
    grd7 :  $\text{Heart.State} = \text{K0}$ 
    grd8 :  $\text{T\_Normal\_Status} = \text{FALSE}$ 

    then
        act1 :  $\text{Disease\_step8} := \text{Probable\_ischemia}$ 
    end

    Event  $T\_Inversion\_Diffuse\_B \hat{=}$ 
           Step 8 B for c.

    extends  $T\_Inversion\_Diffuse\_B$ 

    when
        grd1 :            $\vee$ 
           ( $\forall l, k1. l1 \in \text{LEADS} \wedge k1 \in \text{LEADS} \wedge$ 
            ( $\text{ST\_elevation}(l1) = \text{FALSE} \vee \text{ST\_elevation}(k1) = \text{FALSE}$ )
             $\vee$ 
            ( $\text{ST\_seg\_ele}(l1) < 1000 \vee \text{ST\_seg\_ele}(k1) < 1000$ )
             $\wedge$ 
            ( $\text{Abnormal\_Shaped\_ST}(l1) = \text{FALSE} \vee \text{Abnormal\_Shaped\_ST}(k1) = \text{FALSE}$ ))
             $\Rightarrow l1 \neq k1$ )
    grd2 :  $\forall l. l \in \text{LEADS} \Rightarrow \text{T\_inversion}(l) > 5000$ 
    grd3 :  $\forall l. l \in \text{LEADS} \Rightarrow \text{T\_inversion.l.d}(l) = \text{Diffuse}$ 
    grd4 :  $\text{Heart.State} = \text{K0}$ 
    grd5 :  $\text{T\_Normal\_Status} = \text{FALSE}$ 

    then
        act1 :  $\text{Disease\_step8.B} \in \{\text{Cardiomyopathy, other\_nonspecific}\}$ 
    end

    Event  $Axis\_Assessment\_QRS\_upright\_Yes\_Age\_less\_40 \hat{=}$ 
    extends  $Axis\_Assessment\_QRS\_upright\_Yes\_Age\_less\_40$ 

    any

```

```

    age
  where
    grd1 : QRS_Axis_State(I) = D.Upright ∧
           QRS_Axis_State(aVF) = D.Upright
    grd2 : age ∈ ℕ ∧ age < 40
  then
    act1 : minAngle := 0
    act2 : maxAngle := 110
  end
Event Axis_Assessment_QRS_upright_Yes_Age_gre_40 ≐
extends Axis_Assessment_QRS_upright_Yes_Age_gre_40
  any
    age
  where
    grd1 : QRS_Axis_State(I) = D.Upright ∧
           QRS_Axis_State(aVF) = D.Upright
    grd2 : age ∈ ℕ ∧ age > 40
  then
    act1 : minAngle := -30
    act2 : maxAngle := 90
  end
Event Axis_Assessment_QRS_upright_No_QRS_positive ≐
extends Axis_Assessment_QRS_upright_No_QRS_positive
  when
    grd1 : ¬(QRS_Axis_State(I) = D.Upright ∧
             QRS_Axis_State(aVF) = D.Upright)
    grd2 : QRS_Axis_State(I) = D.Positive ∧
           QRS_Axis_State(aVF) = D.Positive
    grd3 : Heart_State = KO
  then
    act1 : minAngle := -30
    act2 : maxAngle := -90
    act3 : Axis_Devi := LAD
  end
Event Axis_Assessment_QRS_upright_No_QRS_negative ≐
extends Axis_Assessment_QRS_upright_No_QRS_negative
  when
    grd1 : ¬(QRS_Axis_State(I) = D.Upright ∧
             QRS_Axis_State(aVF) = D.Upright)
    grd2 : QRS_Axis_State(I) = D.Negative ∧
           QRS_Axis_State(aVF) = D.Negative
    grd3 : Heart_State = KO
  then
    act1 : minAngle := 110

```

```

    act2 : maxAngle := 180
    act3 : Axis_Devi := RAD
  end
Event Misc_Disease_Step9_LAD  $\hat{=}$ 
extends Misc_Disease_Step9_LAD

  when
    grd1 : Axis_Devi = LAD  $\wedge$ 
           minAngle = -30  $\wedge$ 
           maxAngle = -90
    grd2 : Heart_State = KO
  then
    act1 : Disease_step9  $\in$  {LAFB, MSCHD, Some_Form_VT, ED_OC}
  end

Event Misc_Disease_Step9_RAD  $\hat{=}$ 
refines Misc_Disease_Step9_RAD

  when
    grd1 : Axis_Devi = RAD  $\wedge$ 
           minAngle = 110  $\wedge$ 
           maxAngle = 180
    grd2 : Heart_State = KO
  then
    act1 : Disease_step9  $\in$  {LPFB, NV_MSEC}
  end

Event R_Q_Assessment_R_Abnormal_V56_axis_deviation  $\hat{=}$ 
extends R_Q_Assessment_R_Abnormal_V56_axis_deviation

  when
    grd1 : Q_Wave_State(V5) = TRUE  $\wedge$ 
           Q_Wave_State(V6) = TRUE
    grd2 : Axis_Devi = RAD  $\wedge$ 
           minAngle = 110  $\wedge$ 
           maxAngle = 180
    grd3 : Heart_State = KO
  then
    act1 : Disease_step5 := lateral_MI
  end

Event Miscellaneous_Conditions_Step10  $\hat{=}$ 

  when
    grd1 : MC_Step10_Test_Needed = TRUE
    grd2 : Heart_State = KO
  then
    act1 : Disease_step10  $\in$  {Incomplete_RBBB, Pericarditis, Long_QT, Hypokalemia,
    Digitalis_toxicity, Electrical_alternans, Electronic_pacing, Hypothermia, Hypercalcemia}
  end
end

```

```
Event Misc_Disease_Step10_Dextrcardia_Test  $\hat{=}$   
refines Misc_Disease_Step9_RAD  
  when  
    grd1 : Axis_Devi = RAD  $\wedge$   
             minAngle = 110  $\wedge$   
             maxAngle = 180  
    grd2 : MC_Step10_Test_Needed = TRUE  
    grd3 : Heart_State = KO  
  then  
    act1 : Disease_step9 := Dextrocardia  
  end  
END
```

An Event-B Specification of Step11.ctx
Generated Date: 25 Nov 2010 @ 03:38:53 PM

CONTEXT Step11.ctx

SETS

Disease_Codes_Step11
Disease_Codes_Step11_NW_QRS_T
NW_QRS_Tachycardia_RI QRS Tachcardia Regular or Irregular State

CONSTANTS

Atrial_Premature_Beats
Ventricular_Premature_Beats
Nodal_Premature_Beats
Bradyarrhythmias
Narrow_QRS_Tachycardias
Wide_QRS_Tachycardias
NDS11
Sinus_Tachycardia
AVNRT Atrioventricular nodal reentrant tachycardia (AVNRT)
AF_Fixed_AV_Conduction Atrial flutter (with fixed AV conduction)
AT_Paroxysmal_NParoxysmal Atrial tachycardia (paroxysmal and nonparoxysmal)
WPW_Syndrome_OCMT WPW syndrome (orthodromic circus movement tachycardia)
Atrail_Fibrillation
AF_Variable_AV_Conduction Atrial flutter (with variable AV conduction)
AT_Variable_AV_Block Atrial tachycardia (variable AV block or Wenckebach)
Multifocal_Atrial_Tachycardia
Ventricular_Tachycardia
Supraventricular_Tachycardia Supraventricular tachycardia (with preexisting or functional bundle branch block)
WPW_Syndrome_Orthodromic
Atrial_Tachycardia
WPW_Syndrome_Antidromic
AF_BBB_WPW_Synd_Antidromic Atrial fibrillation (with bundle branch block or with WPW syndrome [antidromic])
AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti Atrial flutter (varying AV conduction, with bundle branch block or WPW syndrome [antidromic])
Torsades_de_pointes
NDS11_NW_QRS
Regular
Irregular

AXIOMS

axm1: $Disease_Codes_Step11 = \{Atrial_Premature_Beats, Ventricular_Premature_Beats, Nodal_Premature_Beats, Bradyarrhythmias, Narrow_QRS_Tachycardias, Wide_QRS_Tachycardias, NDS11\}$
axm2: $\neg Atrial_Premature_Beats = Ventricular_Premature_Beats$

axm3 : \neg Atrial_Premature_Beats = Nodal_Premature_Beats
 axm4 : \neg Atrial_Premature_Beats = Bradyarrhythmias
 axm5 : \neg Atrial_Premature_Beats = Narrow_QRS_Tachycardias
 axm6 : \neg Atrial_Premature_Beats = Wide_QRS_Tachycardias
 axm8 : \neg Atrial_Premature_Beats = NDS11
 axm9 : \neg Ventricular_Premature_Beats = Nodal_Premature_Beats
 axm10 : \neg Ventricular_Premature_Beats = Bradyarrhythmias
 axm11 : \neg Ventricular_Premature_Beats = Narrow_QRS_Tachycardias
 axm12 : \neg Ventricular_Premature_Beats = Wide_QRS_Tachycardias
 axm14 : \neg Ventricular_Premature_Beats = NDS11
 axm15 : \neg Nodal_Premature_Beats = Bradyarrhythmias
 axm16 : \neg Nodal_Premature_Beats = Narrow_QRS_Tachycardias
 axm17 : \neg Nodal_Premature_Beats = Wide_QRS_Tachycardias
 axm19 : \neg Nodal_Premature_Beats = NDS11
 axm20 : \neg Bradyarrhythmias = Narrow_QRS_Tachycardias
 axm21 : \neg Bradyarrhythmias = Wide_QRS_Tachycardias
 axm23 : \neg Bradyarrhythmias = NDS11
 axm24 : \neg Narrow_QRS_Tachycardias = Wide_QRS_Tachycardias
 axm26 : \neg Narrow_QRS_Tachycardias = NDS11
 axm28 : \neg Wide_QRS_Tachycardias = NDS11
 axm29 : Disease_Codes_Step11_NW_QRS_T = {Sinus_Tachycardia, AVNRT, AF_Fixed_AV_Conduction, AT_Paroxysmal_NParoxysmal, WPW_Syndrome_OCMT, Atrial_Fibrillation, AF_Variable_AV_Conduction, AT_Variable_AV_Block, Multifocal_Atrial_Tachycardia, Ventricular_Tachycardia, Supraventricular_Tachycardia, WPW_Syndrome_Orthodromic, Atrial_Tachycardia, WPW_Syndrome_Antidromic, AF_BBB_WPW_Synd_Antidromic, AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti, Torsades_de_pointes, NDS11_NW_QRS}
 axm30 : \neg Sinus_Tachycardia = AVNRT
 axm31 : \neg Sinus_Tachycardia = AF_Fixed_AV_Conduction
 axm32 : \neg Sinus_Tachycardia = AT_Paroxysmal_NParoxysmal
 axm33 : \neg Sinus_Tachycardia = WPW_Syndrome_OCMT
 axm34 : \neg Sinus_Tachycardia = Atrial_Fibrillation
 axm35 : \neg Sinus_Tachycardia = AF_Variable_AV_Conduction
 axm36 : \neg Sinus_Tachycardia = AT_Variable_AV_Block
 axm37 : \neg Sinus_Tachycardia = Multifocal_Atrial_Tachycardia
 axm38 : \neg Sinus_Tachycardia = Ventricular_Tachycardia
 axm39 : \neg Sinus_Tachycardia = Supraventricular_Tachycardia
 axm40 : \neg Sinus_Tachycardia = WPW_Syndrome_Orthodromic
 axm41 : \neg Sinus_Tachycardia = Atrial_Tachycardia
 axm42 : \neg Sinus_Tachycardia = WPW_Syndrome_Antidromic
 axm43 : \neg Sinus_Tachycardia = AF_BBB_WPW_Synd_Antidromic
 axm44 : \neg Sinus_Tachycardia = AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti
 axm45 : \neg Sinus_Tachycardia = Torsades_de_pointes
 axm46 : \neg Sinus_Tachycardia = NDS11_NW_QRS
 axm47 : \neg AVNRT = AF_Fixed_AV_Conduction

axm48 : $\neg AVNRT = AT_Paroxysmal_NParoxysmal$
 axm49 : $\neg AVNRT = WPW_Syndrome_OCMT$
 axm50 : $\neg AVNRT = Atrial_Fibrillation$
 axm51 : $\neg AVNRT = AF_Variable_AV_Conduction$
 axm52 : $\neg AVNRT = AT_Variable_AV_Block$
 axm53 : $\neg AVNRT = Multifocal_Atrial_Tachycardia$
 axm54 : $\neg AVNRT = Ventricular_Tachycardia$
 axm55 : $\neg AVNRT = Supraventricular_Tachycardia$
 axm56 : $\neg AVNRT = WPW_Syndrome_Orthodromic$
 axm57 : $\neg AVNRT = Atrial_Tachycardia$
 axm58 : $\neg AVNRT = WPW_Syndrome_Antidromic$
 axm59 : $\neg AVNRT = AF_BBB_WPW_Synd_Antidromic$
 axm60 : $\neg AVNRT = AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti$
 axm61 : $\neg AVNRT = Torsades_de_pointes$
 axm62 : $\neg AVNRT = NDS11_NW_QRS$
 axm63 : $\neg AF_Fixed_AV_Conduction = AT_Paroxysmal_NParoxysmal$
 axm64 : $\neg AF_Fixed_AV_Conduction = WPW_Syndrome_OCMT$
 axm65 : $\neg AF_Fixed_AV_Conduction = Atrial_Fibrillation$
 axm66 : $\neg AF_Fixed_AV_Conduction = AF_Variable_AV_Conduction$
 axm67 : $\neg AF_Fixed_AV_Conduction = AT_Variable_AV_Block$
 axm68 : $\neg AF_Fixed_AV_Conduction = Multifocal_Atrial_Tachycardia$
 axm69 : $\neg AF_Fixed_AV_Conduction = Ventricular_Tachycardia$
 axm70 : $\neg AF_Fixed_AV_Conduction = Supraventricular_Tachycardia$
 axm71 : $\neg AF_Fixed_AV_Conduction = WPW_Syndrome_Orthodromic$
 axm72 : $\neg AF_Fixed_AV_Conduction = Atrial_Tachycardia$
 axm73 : $\neg AF_Fixed_AV_Conduction = WPW_Syndrome_Antidromic$
 axm74 : $\neg AF_Fixed_AV_Conduction = AF_BBB_WPW_Synd_Antidromic$
 axm75 : $\neg AF_Fixed_AV_Conduction = AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti$
 axm76 : $\neg AF_Fixed_AV_Conduction = Torsades_de_pointes$
 axm77 : $\neg AF_Fixed_AV_Conduction = NDS11_NW_QRS$
 axm78 : $\neg AT_Paroxysmal_NParoxysmal = WPW_Syndrome_OCMT$
 axm79 : $\neg AT_Paroxysmal_NParoxysmal = Atrial_Fibrillation$
 axm80 : $\neg AT_Paroxysmal_NParoxysmal = AF_Variable_AV_Conduction$
 axm81 : $\neg AT_Paroxysmal_NParoxysmal = AT_Variable_AV_Block$
 axm82 : $\neg AT_Paroxysmal_NParoxysmal = Multifocal_Atrial_Tachycardia$
 axm83 : $\neg AT_Paroxysmal_NParoxysmal = Ventricular_Tachycardia$
 axm84 : $\neg AT_Paroxysmal_NParoxysmal = Supraventricular_Tachycardia$
 axm85 : $\neg AT_Paroxysmal_NParoxysmal = WPW_Syndrome_Orthodromic$
 axm86 : $\neg AT_Paroxysmal_NParoxysmal = Atrial_Tachycardia$
 axm87 : $\neg AT_Paroxysmal_NParoxysmal = WPW_Syndrome_Antidromic$
 axm88 : $\neg AT_Paroxysmal_NParoxysmal = AF_BBB_WPW_Synd_Antidromic$
 axm89 : $\neg AT_Paroxysmal_NParoxysmal = AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti$
 axm90 : $\neg AT_Paroxysmal_NParoxysmal = Torsades_de_pointes$
 axm91 : $\neg AT_Paroxysmal_NParoxysmal = NDS11_NW_QRS$

axm92 : \neg WPW_Syndrome_OCMT = Atrial_Fibrillation
 axm93 : \neg WPW_Syndrome_OCMT = AF_Variable_AV_Conduction
 axm94 : \neg WPW_Syndrome_OCMT = AT_Variable_AV_Block
 axm95 : \neg WPW_Syndrome_OCMT = Multifocal_Atrial_Tachycardia
 axm96 : \neg WPW_Syndrome_OCMT = Ventricular_Tachycardia
 axm97 : \neg WPW_Syndrome_OCMT = Supraventricular_Tachycardia
 axm98 : \neg WPW_Syndrome_OCMT = WPW_Syndrome_Orthodromic
 axm99 : \neg WPW_Syndrome_OCMT = Atrial_Tachycardia
 axm100 : \neg WPW_Syndrome_OCMT = WPW_Syndrome_Antidromic
 axm101 : \neg WPW_Syndrome_OCMT = AF_BBB_WPW_Synd_Antidromic
 axm102 : \neg WPW_Syndrome_OCMT = AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti
 axm103 : \neg WPW_Syndrome_OCMT = Torsades_de_pointes
 axm104 : \neg WPW_Syndrome_OCMT = NDS11_NW_QRS
 axm105 : \neg Atrial_Fibrillation = AF_Variable_AV_Conduction
 axm106 : \neg Atrial_Fibrillation = AT_Variable_AV_Block
 axm107 : \neg Atrial_Fibrillation = Multifocal_Atrial_Tachycardia
 axm108 : \neg Atrial_Fibrillation = Ventricular_Tachycardia
 axm109 : \neg Atrial_Fibrillation = Supraventricular_Tachycardia
 axm110 : \neg Atrial_Fibrillation = WPW_Syndrome_Orthodromic
 axm111 : \neg Atrial_Fibrillation = Atrial_Tachycardia
 axm112 : \neg Atrial_Fibrillation = WPW_Syndrome_Antidromic
 axm113 : \neg Atrial_Fibrillation = AF_BBB_WPW_Synd_Antidromic
 axm114 : \neg Atrial_Fibrillation = AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti
 axm115 : \neg Atrial_Fibrillation = Torsades_de_pointes
 axm116 : \neg Atrial_Fibrillation = NDS11_NW_QRS
 axm117 : \neg AF_Variable_AV_Conduction = AT_Variable_AV_Block
 axm118 : \neg AF_Variable_AV_Conduction = Multifocal_Atrial_Tachycardia
 axm119 : \neg AF_Variable_AV_Conduction = Ventricular_Tachycardia
 axm120 : \neg AF_Variable_AV_Conduction = Supraventricular_Tachycardia
 axm121 : \neg AF_Variable_AV_Conduction = WPW_Syndrome_Orthodromic
 axm122 : \neg AF_Variable_AV_Conduction = Atrial_Tachycardia
 axm123 : \neg AF_Variable_AV_Conduction = WPW_Syndrome_Antidromic
 axm124 : \neg AF_Variable_AV_Conduction = AF_BBB_WPW_Synd_Antidromic
 axm125 : \neg AF_Variable_AV_Conduction = AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti
 axm126 : \neg AF_Variable_AV_Conduction = Torsades_de_pointes
 axm127 : \neg AF_Variable_AV_Conduction = NDS11_NW_QRS
 axm128 : \neg AT_Variable_AV_Block = Multifocal_Atrial_Tachycardia
 axm129 : \neg AT_Variable_AV_Block = Ventricular_Tachycardia
 axm130 : \neg AT_Variable_AV_Block = Supraventricular_Tachycardia
 axm131 : \neg AT_Variable_AV_Block = WPW_Syndrome_Orthodromic
 axm132 : \neg AT_Variable_AV_Block = Atrial_Tachycardia
 axm133 : \neg AT_Variable_AV_Block = WPW_Syndrome_Antidromic
 axm134 : \neg AT_Variable_AV_Block = AF_BBB_WPW_Synd_Antidromic
 axm135 : \neg AT_Variable_AV_Block = AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti

axm136 : \neg AT_Variable_AV_Block = Torsades_de_pointes
 axm137 : \neg AT_Variable_AV_Block = NDS11_NW_QRS
 axm138 : \neg Multifocal_Atrial_Tachycardia = Ventricular_Tachycardia
 axm139 : \neg Multifocal_Atrial_Tachycardia = Supraventricular_Tachycardia
 axm140 : \neg Multifocal_Atrial_Tachycardia = WPW_Syndrome_Orthodromic
 axm141 : \neg Multifocal_Atrial_Tachycardia = Atrial_Tachycardia
 axm142 : \neg Multifocal_Atrial_Tachycardia = WPW_Syndrome_Antidromic
 axm143 : \neg Multifocal_Atrial_Tachycardia = AF_BBB_WPW_Synd_Antidromic
 axm144 : \neg Multifocal_Atrial_Tachycardia = AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti
 axm145 : \neg Multifocal_Atrial_Tachycardia = Torsades_de_pointes
 axm146 : \neg Multifocal_Atrial_Tachycardia = NDS11_NW_QRS
 axm147 : \neg Ventricular_Tachycardia = Supraventricular_Tachycardia
 axm148 : \neg Ventricular_Tachycardia = WPW_Syndrome_Orthodromic
 axm149 : \neg Ventricular_Tachycardia = Atrial_Tachycardia
 axm150 : \neg Ventricular_Tachycardia = WPW_Syndrome_Antidromic
 axm151 : \neg Ventricular_Tachycardia = AF_BBB_WPW_Synd_Antidromic
 axm152 : \neg Ventricular_Tachycardia = AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti
 axm153 : \neg Ventricular_Tachycardia = Torsades_de_pointes
 axm154 : \neg Ventricular_Tachycardia = NDS11_NW_QRS
 axm155 : \neg Supraventricular_Tachycardia = WPW_Syndrome_Orthodromic
 axm156 : \neg Supraventricular_Tachycardia = Atrial_Tachycardia
 axm157 : \neg Supraventricular_Tachycardia = WPW_Syndrome_Antidromic
 axm158 : \neg Supraventricular_Tachycardia = AF_BBB_WPW_Synd_Antidromic
 axm159 : \neg Supraventricular_Tachycardia = AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti
 axm160 : \neg Supraventricular_Tachycardia = Torsades_de_pointes
 axm161 : \neg Supraventricular_Tachycardia = NDS11_NW_QRS
 axm162 : \neg WPW_Syndrome_Orthodromic = Atrial_Tachycardia
 axm163 : \neg WPW_Syndrome_Orthodromic = WPW_Syndrome_Antidromic
 axm164 : \neg WPW_Syndrome_Orthodromic = AF_BBB_WPW_Synd_Antidromic
 axm165 : \neg WPW_Syndrome_Orthodromic = AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti
 axm166 : \neg WPW_Syndrome_Orthodromic = Torsades_de_pointes
 axm167 : \neg WPW_Syndrome_Orthodromic = NDS11_NW_QRS
 axm168 : \neg Atrial_Tachycardia = WPW_Syndrome_Antidromic
 axm169 : \neg Atrial_Tachycardia = AF_BBB_WPW_Synd_Antidromic
 axm170 : \neg Atrial_Tachycardia = AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti
 axm171 : \neg Atrial_Tachycardia = Torsades_de_pointes
 axm172 : \neg Atrial_Tachycardia = NDS11_NW_QRS
 axm173 : \neg WPW_Syndrome_Antidromic = AF_BBB_WPW_Synd_Antidromic
 axm174 : \neg WPW_Syndrome_Antidromic = AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti
 axm175 : \neg WPW_Syndrome_Antidromic = Torsades_de_pointes
 axm176 : \neg WPW_Syndrome_Antidromic = NDS11_NW_QRS
 axm177 : \neg AF_BBB_WPW_Synd_Antidromic = AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti
 axm178 : \neg AF_BBB_WPW_Synd_Antidromic = Torsades_de_pointes
 axm179 : \neg AF_BBB_WPW_Synd_Antidromic = NDS11_NW_QRS

axm180 : $\neg AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti = Torsades_de_pointes$
axm181 : $\neg AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti = NDS11_NW_QRS$
axm182 : $\neg Torsades_de_pointes = NDS11_NW_QRS$
axm183 : $NW_QRS_Tachycardia_RI = \{Regular, Irregular\}$
axm184 : $\neg Regular = Irregular$

END

An Event-B Specification of Step_11_Abnormal_Rhythm
Generated Date: 25 Nov 2010 @ 03:39:50 PM

MACHINE Step_11_Abnormal_Rhythm

REFINES Step10_Miscellaneous_conditions

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx, Step8_ctx, Step9, Step10_ctx, Step11_ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
Small_R_QS A small R or QS wave in V1 and V2
Slurred_S_duration Slurred S duration
Delta_Wave Delta Wave
Disease_step3
ST_elevation ST segment elevation (Coved or Saddle-back)
Epsilon_Wave Epsilon Wave or (a terminal notch in the QRS)
ST_seg_ele ST segment for elevation 1mm=0.1mV
Disease_step4
Q_Width Q wave width
Q_Depth Q wave depth
Q_Normal_Status Q wave normal or abnormal
Age_of_Inf Age of Infarct
Disease_step5
Mice_State
R_Depth R wave depth or height (also use in Step 7)
R_Normal_Status R wave normal or abnormal
Q_Wave_State Q wave states for all LEADS
P_Wave_Peak function to estimate the peak of LEADS signal
Disease_step6
PP_Interval
RR_Interval
Diphasic
P_Wave_Broad

S_Depth S wave depth or height
 R_S_Ratio R wave and S wave Ratio function
 T_Wave_State T wave patterns...
 Disease_step8
 T_Wave_State_B B for alternative method of T wave assessment
 T_Normal_Status T wave normal or abnormal
 Abnormal_Shaped_ST
 Asy_T_Inversion_strain Asymmetric T wave Inversion strain pattern
 T_inversion Deep T wave inversion
 T_inversion_l_d T inversion Localized and Diffuse
 Disease_step8_B
 QRS_Axis_State QRS Axis Direction
 minAngle min. value of angle of Axis in degree
 maxAngle max. value of angle of Axis in degree
 Axis_Devi Axis Deviation in LEADS...
 Disease_step9
 Disease_step10
 MC_Step10_Test_Needed Miscellaneous Conditions test in Step 10
 Disease_step11
 ST_depression

INVARIANTS

inv1 : $Disease_step11 \in Disease_Codes_Step11$
inv2 : $Sinus = Yes \wedge Disease_step11 \in \{Atrial_Premature_Beats, Ventricular_Premature_Beats, Nodal_Premature_Beats, Bradyarrhythmias, Narrow_QRS_Tachycardias, Wide_QRS_Tachycardias\}$
 $\Rightarrow Heart_State = KO$

EVENTS

Initialisation

extended

begin

act1 : $RR_Int_equidistant : \in LEADS \rightarrow BOOL$
act2 : $PP_Int_equidistant : \in LEADS \rightarrow BOOL$
act3 : $P_Positive : \in LEADS \rightarrow BOOL$
act4 : $Sinus := No$
act5 : $PP_Interval : \in LEADS \rightarrow \mathbb{N}$
act6 : $RR_Interval : \in LEADS \rightarrow \mathbb{N}$
act7 : $Heart_Rate : \in 1..300$
act8 : $Heart_State := KO$
act9 : $PR_Int := 120$
act10 : $Disease_step2 := NDS2$
act11 : $QRS_Int := 50$
act12 : $Notched_R : \in LEADS \rightarrow BOOL$
act13 : $Small_R_QS : \in LEADS \rightarrow BOOL$
act14 : $Slurred_S_duration : \in LEADS \rightarrow \mathbb{N}_1$
act15 : $M_Shape_Complex : \in LEADS \rightarrow BOOL$
act16 : $Slurred_S : \in LEADS \rightarrow BOOL$

```

act17 : ST_elevation :∈ LEADS → BOOL
act18 : Epsilon_Wave :∈ LEADS → BOOL
act19 : Delta_Wave := 0
act20 : Disease_step3 := NDS3
act21 : ST_seg_ele :∈ LEADS → ℕ
act22 : Disease_step4 := NDS4
act57 : ST_depression :∈ LEADS → ℕ
act23 : Q_Width :∈ LEADS → ℕ
act24 : Q_Depth :∈ LEADS → ℕ
act25 : Q_Normal_Status := FALSE
act26 : Mice_State := NMS
act27 : R_Depth :∈ LEADS → ℕ
act28 : R_Normal_Status := FALSE
act29 : Q_Wave_State :∈ LEADS → BOOL
act30 : Age_of_Inf :∈ Age_of_Infarct
act31 : Disease_step5 := NDS5
act32 : Diphasic :∈ LEADS → BOOL
act33 : P_Wave_Broad :∈ LEADS → ℕ
act34 : P_Wave_Peak :∈ LEADS → ℕ
act35 : Disease_step6 := NDS6
act36 : S_Depth :∈ LEADS → ℕ
act37 : R_S_Ratio :∈ LEADS → ℕ
act38 : T_Wave_State :∈ LEADS → T_State
act39 : Disease_step8 := NDS8
act40 : Abnormal_Shaped_ST :∈ LEADS → BOOL
act41 : Asy_T_Inversion_strain :∈ LEADS → BOOL
act43 : T_inversion_l_d :∈ LEADS → T_State_l_d
act42 : T_inversion :∈ LEADS → ℕ
act44 : Disease_step8_B := NDS8B
act45 : T_Wave_State_B :∈ LEADS → T_State_B
act46 : T_Normal_Status := FALSE
act47 : QRS_Axis_State :∈ LEADS → QRS_directions
act48 : minAngle := 0
act49 : maxAngle := 0
act50 : Axis_Devi := ND
act51 : Disease_step9 := NDS9
act52 : Disease_step10 := NDS10
act53 : MC_Step10_Test_Needed := FALSE
act54 : Disease_step11 := NDS11

```

end

Event *Rhythm_test_TRUE* $\hat{=}$
Sinus Rhythm with Normal Rate

extends *Rhythm_test_TRUE*

any

rate

where

```

grd1 : ( $\exists l. l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
      RR_Int_equidistant(l) = TRUE  $\wedge$ 
      RR_Interval(l) = PP_Interval(l))
       $\wedge$ 
      P_Positive(II) = TRUE
grd4 : rate  $\in$  60 .. 100
      60..100 is the range of normal heart rate
grd5 : PR_Int  $\leq$  200
      Heart is Normal if PR  $\leq$  200 QRS_Int  $<$  120
      Heart is Normal if QRS  $<$  120
grd6 : Disease_step2 = NDS2
grd7 : Disease_step3 = NDS3
grd8 : Disease_step4 = NDS4
grd9 : Disease_step5 = NDS5
grd10 : Disease_step6 = NDS6
grd11 : Disease_step8 = NDS8
grd12 : Disease_step8_B = NDS8B
grd13 : Disease_step9 = NDS9
grd14 : Disease_step10 = NDS10
grd15 : Disease_step11 = NDS11
then
  act1 : Sinus := Yes
  act2 : Heart_Rate := rate
  act3 : Heart_State := OK
end

Event Rhythm_test_FALSE  $\hat{=}$ 
  Abnormal Rhythm with Rate

extends Rhythm_test_FALSE

any
  rate
where
  grd1 : ( $\forall l. l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \vee$ 
        RR_Int_equidistant(l) = FALSE  $\vee$ 
        RR_Interval(l)  $\neq$  PP_Interval(l))
         $\vee$ 
        P_Positive(II) = FALSE
  grd2 : rate  $\in$  1 .. 300
then
  act1 : Sinus := No
  act2 : Heart_Rate := rate
  act3 : Heart_State := KO
end

Event Rhythm_test_TRUE_Rate  $\hat{=}$ 
  Sinus Rhythm with abnormal Rate

extends Rhythm_test_TRUE_Rate

any
  rate

```

```

where
  grd1 : ( $\exists l. l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
    RR_Int_equidistant(l) = TRUE  $\wedge$ 
    RR_Interval(l) = PP_Interval(l))
     $\wedge$ 
    P_Positive(II) = TRUE
  grd5 : rate  $\in 1..300 \setminus 60..100$ 
    60..100 is the range of normal heart rate, so rest of no. is abnormal
  grd6 : Disease_step3 = WPW_Syndrome  $\vee$  Disease_step3 = Brugada_Syndrome  $\vee$ 
    Disease_step3 = RV_Dysplasia  $\vee$  Disease_step3 = IVCD

then
  act1 : Sinus := Yes
  act2 : Heart_Rate := rate
  act3 : Heart_State := KO

end

Event PR_Test  $\hat{=}$ 
  PR_Interval_Test

extends PR_Test

any
  pr

where
  grd1 : pr  $\in 120..220$ 
    time interval in (ms.)
  grd2 : pr > 200
  grd3 : Sinus = Yes
  grd4 : Heart_State = KO

then
  act1 : PR_Int := pr
  act2 : Disease_step2 := First_degree_AV_Block

end

Event QRS_Test_LBBB  $\hat{=}$ 
  QRS_Complex_Interval_Test

extends QRS_Test_LBBB

any
  qrs

where
  grd1 : qrs  $\in 50..150$ 
  grd2 : qrs  $\geq 120$ 
  grd3 : Sinus = Yes
  grd4 : Heart_State = KO
  grd5 : Notched_R(I) = TRUE  $\wedge$ 
    Notched_R(V5) = TRUE  $\wedge$ 
    Notched_R(V6) = TRUE
    Right_Bundle_Branch_Block (RBBB)
  grd6 : Small_R_QS(V1) = TRUE  $\wedge$ 
    Small_R_QS(V2) = TRUE

```

```

    grd7 : Q_Wave_State(V1) = TRUE ∧
           Q_Wave_State(V2) = TRUE ∧
           Q_Wave_State(V3) = TRUE ∧
           Q_Wave_State(V4) = TRUE
           from step 5
    grd8 : R_Normal_Status = FALSE
           from step 5
    grd9 : Axis_Devi = LAD ∧
           minAngle = -30 ∧
           maxAngle = -90
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := LBBB
  end

Event QRS_Test_RBBB ≐
  Right Bundle Branch Block (RBBB)

extends QRS_Test_RBBB

  any
    qrs
  where
    grd1 : qrs ∈ 50 .. 150
    grd2 : qrs ≥ 120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : M_Shape_Complex(V1) = TRUE ∧
           M_Shape_Complex(V2) = TRUE
    grd7 : Slurred_S(I) = TRUE ∧
           Slurred_S(V5) = TRUE ∧
           Slurred_S(V6) = TRUE
    grd8 : Slurred_S_duration(I) > 40 ∧
           Slurred_S_duration(V5) > 40 ∧
           Slurred_S_duration(V6) > 40
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := RBBB
  end

Event QRS_Test_Atypical_RLBBB_WPW_Syndrome ≐
  QRS Test for Atypical LBBB RBBB

extends QRS_Test_Atypical_RLBBB_WPW_Syndrome

  any
    sympt
    d_wave
    exmi
  where
    grd1 : QRS_Int ≥ 110
    grd2 : sympt = A_RBBB ∨ sympt = A_LBBB
    grd3 : d_wave ∈ ℕ

```



```

    grd4 : (d_wave + PR_Int) ≤ 120
           Delta_Wave + PR ≤ 120 Heart_State = KO
    grd5 : Disease_step4 = Acute_inferior_MI
    grd6 : Disease_step4 = Acute_inferior_MI
    grd7 : exmi ∈ Mice_State5 ∧ exmi = Exclude_Mimics_MI
  then
    act2 : Delta_Wave := d_wave
    act3 : Disease_step3 := WPW_Syndrome
  end

Event QRS_Test_Atypical_RBBB_Brugada_Syndrome ≐
  Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends QRS_Test_Atypical_RBBB_Brugada_Syndrome

  any
    sympt
    dis
  where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int ≥ 110
    grd4 : Slurred_S(V5) = FALSE ∧
           Slurred_S(V6) = FALSE
    grd5 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, NDS3}
    grd6 : ST_elevation(V1) = TRUE ∧
           ST_elevation(V2) = TRUE
    grd7 : Sinus = Yes
  then
    act1 : Disease_step3 := Brugada_Syndrome
  end

Event QRS_Test_Atypical_RBBB_RV_Dysplasia ≐
  Right Ventricular Dysplasia

extends QRS_Test_Atypical_RBBB_RV_Dysplasia

  any
    sympt
    dis
  where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int ≥ 110
    grd4 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, NDS3}
    grd5 : Epsilon_Wave(V1) = TRUE ∧
           Epsilon_Wave(V3) = TRUE
  then
    act1 : Disease_step3 := RV_Dysplasia
  end

Event QRS_Test_Atypical_RBBB_IVCD ≐
  IVCD diagnosis

```

```

extends QRS_Test_Atypical_RBBB_IVCD

  any
    dis
  where
    grd1 : QRS_Int ≥ 110
    grd2 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, NDS3}
    grd3 : Heart_State = KO
  then
    act1 : Disease_step3 := IVCD
  end

Event ST_seg_elevation_YES ≐
  ST segment elevation...

extends ST_seg_elevation_YES

  when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :
      ∨
      ((∃ l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
      (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
      ∧
      (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
      ∧ l1 ≠ k1
      ∧
      (
      (l1 = V1 ∧ k1 = V2) ∨
      (l1 = V2 ∧ k1 = V3) ∨
      (l1 = V3 ∧ k1 = V4) ∨
      (l1 = V4 ∧ k1 = V5) ∨
      (l1 = V5 ∧ k1 = V6)
      )
      ))
  grd4 : Disease_step4 ∈ {Acute_inferior_MI, Acute_anterior_MI}
  then
    act1 : Disease_step4 := STEMI
  end

Event ST_seg_elevation_NOTCKMB_Yes ≐
  Troponin or CK-MB positive YES

extends ST_seg_elevation_NOTCKMB_Yes

  when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :
      ∨
      (∀ l1 · l1 ∈ {II, III, aVF} ⇒
      (ST_elevation(l1) = FALSE ∧ ST_seg_ele(l1) < 1000))
  grd4 : ∃ l, k · l ∈ LEADS ∧ k ∈ LEADS ∧
    (ST_depression(l) ≥ 1000 ∧ ST_depression(k) ≥ 1000)
    ∧ l ≠ k
  grd5 : Disease_step4 ∈ {Troponin, CK_MB}

```

```

    then
      act1 : Disease_step4 := Non_STEMI
    end

Event ST_seg_elevation_NO_TCKMB_No  $\hat{=}$ 
  Troponin or CK-MB positive No

extends ST_seg_elevation_NO_TCKMB_No

  when

    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :  $\vee$ 
      ( $\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$ 
      (ST_elevation(l1) = FALSE  $\wedge$  ST_seg_ele(l1) < 1000))
    grd4 :  $\exists l, k \cdot l \in \text{LEADS} \wedge k \in \text{LEADS} \wedge$ 
      (ST_depression(l)  $\geq$  1000  $\wedge$  ST_depression(k)  $\geq$  1000)
       $\wedge l \neq k$ 
    grd5 : Disease_step4  $\notin$  {Troponin, CK_MB}
    grd6 :  $\forall l \cdot l \in \text{LEADS} \Rightarrow \text{T\_inversion}(l) < 5000$ 
    grd7 : T_Normal_Status = FALSE

    then
      act1 : Disease_step4 := Ischemia
    end

Event Q_Assessment_Normal  $\hat{=}$ 
  Q wave assessment normal

extends Q_Assessment_Normal

  when

    grd1 : Q_Width(II) < 40  $\wedge$  Q_Depth(II)  $\leq$  3000  $\wedge$ 
      Q_Width(aVF) < 40  $\wedge$  Q_Depth(aVF)  $\leq$  3000  $\wedge$ 
      Q_Width(aVL) < 40
      1000 micrometer = 1 millimeter
    grd2 : Q_Width(III)  $\leq$  40  $\wedge$  Q_Depth(III)  $\leq$  7000  $\wedge$  Q_Depth(aVL)  $\leq$  7000
    grd3 : Q_Depth(I) < 40  $\wedge$  Q_Depth(I)  $\leq$  1500

    then
      act1 : Q_Normal_Status := TRUE
    end

Event Q_Assessment_Abnormal_AMI  $\hat{=}$ 
  Q wave assessment abnormal for anterolateral MI (AMI)

extends Q_Assessment_Abnormal_AMI

  when

    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :  $\vee$ 
      ( $\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
      (ST_elevation(l1) = TRUE  $\wedge$  ST_elevation(k1) = TRUE)
       $\wedge$ 
      (ST_seg_ele(l1)  $\geq$  1000  $\wedge$  ST_seg_ele(k1)  $\geq$  1000)
       $\wedge l1 \neq k1$ 

```

```

    ^
    (
    (l1 = V1 ∧ k1 = V2) ∨
    (l1 = V2 ∧ k1 = V3) ∨
    (l1 = V3 ∧ k1 = V4) ∨
    (l1 = V4 ∧ k1 = V5) ∨
    (l1 = V5 ∧ k1 = V6)
    )
  ))
grd4 : Q_Width(V5) ≥ 40 ∧ Q_Depth(V5) > 3000 ∧
      Q_Width(V6) ≥ 40 ∧ Q_Depth(V6) > 3000
grd5 : Q_Width(aVL) ≥ 40 ∧ Q_Depth(aVL) > 7000
grd6 : Q_Depth(I) ≥ 40 ∧ Q_Depth(I) > 1500
grd7 : Q_Normal_Status = FALSE
  then
    act1 : Disease_step4 := Acute_anterior_MI
  end

Event Q_Assessment_Abnormal_IMI ≐
  Q wave assessment abnormal for inferior MI (IMI)

extends Q_Assessment_Abnormal_IMI

when
  grd1 : Heart_State = KO
  grd2 : Sinus = Yes
  grd3 :
    ∨
    ((∃l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
    (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
    ∧
    (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
    ∧ l1 ≠ k1
    ∧
    (
    (l1 = V1 ∧ k1 = V2) ∨
    (l1 = V2 ∧ k1 = V3) ∨
    (l1 = V3 ∧ k1 = V4) ∨
    (l1 = V4 ∧ k1 = V5) ∨
    (l1 = V5 ∧ k1 = V6)
    )
    ))
grd4 : Q_Width(II) ≥ 40 ∧ Q_Depth(II) > 3000 ∧
      Q_Width(III) > 40 ∧ Q_Depth(III) > 7000 ∧
      Q_Width(aVF) ≥ 40 ∧ Q_Depth(aVF) > 3000
grd5 : Q_Normal_Status = FALSE
  then
    act1 : Disease_step4 := Acute_inferior_MI
  end

Event Determine_Age_of_Infarct ≐
extends Determine_Age_of_Infarct

when

```

```

    grd1 : Disease_step4 = Acute_inferior_MI
           ∨
           Disease_step5 ∈ {anterior_MI, LVH, emphysema}
           ∨
           Mice_State = Exclude_Mimics_MI
           ∨
           Disease_step2 = LBBB
  then
    act1 : Age_of_Inf :∈ {recent, old, indeterminate}
  end
Event Exclude_Mimics ≐
extends Exclude_Mimics

  any
    exmi
  where
    grd1 : Disease_step4 = Acute_inferior_MI
    grd2 : exmi ∈ Mice_State5 ∧ exmi = Exclude_Mimics_MI
  then
    act1 : Disease_step5 := Hypertrophic_cardiomyopathy
    act2 : Mice_State := borderline_Qs
  end

Event R_Assessment_Normal ≐
  Q wave assessment normal
extends R_Assessment_Normal

  any
    age
  where
    grd1 : R.Depth(V1) ≥ 0 ∧ R.Depth(V1) ≤ 6000 ∧ age > 30
           1000 micrometer = 1 millimeter
    grd2 : R.Depth(V2) > 200 ∧ R.Depth(V2) ≤ 12000
    grd3 : R.Depth(V2) ≥ 1000 ∧ R.Depth(V2) ≤ 24000
  then
    act1 : R.Normal_Status := TRUE
  end

Event R_Assessment_Abnormal ≐
extends R_Assessment_Abnormal

  when
    grd1 : R.Normal_Status = FALSE
  then
    act1 : Mice_State :∈ {late_transition, normal_variant}
  end

Event R_Q_Assessment_R_Abnormal_V1234 ≐
  R wave abnormal , pathologic Q waves consider in V1-V4
extends R_Q_Assessment_R_Abnormal_V1234

```

```

when
  grd1 : R.Normal_Status = FALSE
  grd2 : Q_Wave_State(V1) = TRUE ∧
        Q_Wave_State(V2) = TRUE ∧
        Q_Wave_State(V3) = TRUE ∧
        Q_Wave_State(V4) = TRUE
  grd3 : Heart_State = KO
then
  act1 : Disease_step5 ∈ {anterior_MI, LVH, emphysema}
  act2 : Mice_State := Exclude_Mimics_MI
end

Event R_Q_Assessment_R_Abnormal_V56 ≐
  R wave abnormal , pathologic Q waves consider in V5-V6

extends R_Q_Assessment_R_Abnormal_V56

when
  grd1 : Q_Wave_State(V5) = TRUE ∧
        Q_Wave_State(V6) = TRUE
  grd2 : Heart_State = KO
then
  act1 : Disease_step5 := Hypertrophic_cardiomyopathy
end

Event P_Wave_assessment_Peaked_Broad_No ≐

extends P_Wave_assessment_Peaked_Broad_No

when
  grd1 : (P_Wave_Peak(II) < 3000 ∧
        P_Wave_Peak(V1) < 3000)
        ∨
        (P_Wave_Broad(II) < 110 ∧ P_Wave_Broad(V1) < 110) ∨
        Diphasic(II) = FALSE ∨
        Diphasic(V1) = FALSE
then
  act1 : Disease_step6 := NDS6
end

Event P_Wave_assessment_Peaked_Yes ≐

extends P_Wave_assessment_Peaked_Yes

when
  grd1 : P_Wave_Peak(II) ≥ 3000
  grd2 : P_Wave_Peak(V1) ≥ 3000
  grd3 : Heart_State = KO
then
  act1 : Disease_step6 := RAE
end

Event P_Wave_assessment_Peaked_Yes_Check_RAE ≐

extends P_Wave_assessment_Peaked_Yes_Check_RAE

```

```

when
  grd1 : P.Wave.Peak(II) ≥ 3000
  grd2 : P.Wave.Peak(V1) ≥ 3000
  grd3 : Disease_step6 = RAE
  grd4 : Heart_State = KO
then
  act1 : Disease_step6 := RV_strain
end
Event P_Wave_assessment_Broad_Yes ≐
extends P_Wave_assessment_Broad_Yes
when
  grd1 : (P.Wave.Broad(II) ≥ 110 ∧ P.Wave.Broad(V1) ≥ 110) ∨
    Diphasic(II) = TRUE ∨
    Diphasic(V1) = TRUE
  grd2 : Heart_State = KO
then
  act1 : Disease_step6 := LAE
end
Event P_Wave_assessment_Broad_Yes_Check_LAE ≐
extends P_Wave_assessment_Broad_Yes_Check_LAE
when
  grd1 : (P.Wave.Broad(II) ≥ 110 ∧ P.Wave.Broad(V1) ≥ 110) ∨
    Diphasic(II) = TRUE ∨
    Diphasic(V1) = TRUE
  grd2 : Disease_step6 = LAE
  grd3 : Heart_State = KO
then
  act1 : Disease_step6 ∈ {mitral_stenosis, mitral_regurgitation,
    LV_failure, dilated_cardiomyopathy}
end
Event LVH_Assessment ≐
LVH_Assessment
extends LVH_Assessment
any
  LVH_specificity    specificity in percentage
  sensitivity        sensitivity in percentage
  sex
where
  grd1 : (P.Wave.Broad(II) ≥ 110 ∧ P.Wave.Broad(V1) ≥ 110) ∨
    Diphasic(II) = TRUE ∨
    Diphasic(V1) = TRUE
  grd2 : Disease_step6 = LAE
  grd5 : sex ∈ {0, 1}
    o for men and 1 for women

```

```

    grd3 : ((S_Depth(V1) + R_Depth(V5)) > 35000
            ∨
            (S_Depth(V1) + R_Depth(V6)) > 35000)
            1mm = 1000 micrometer..... 1 assessment
    grd4 : ((R_Depth(aVL) + S_Depth(V1) ≥ 24000) ∧ sex = 0)
            ∨
            ((R_Depth(aVL) + S_Depth(V1) ≥ 18000) ∧ sex = 1)
            2 assessment
    grd6 : LVH_specificity = 90
            ∧
            sensitivity < 40
            1 and 2 assessment
    grd7 : Disease_step6 = LAE ⇒ LVH_specificity < 98
            3 assessment
    grd8 :      (∀t.t ∈ LEADS ⇒ ST_elevation(t) = TRUE
            ∨
            Q_Normal_Status = FALSE))
            A or B : from step 8 development
    grd9 :      ∨
            (∀l1,k1.l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
            ((ST_elevation(l1) = FALSE ∨ ST_elevation(k1) = FALSE)
            ∨
            ((ST_seg_ele(l1) < 1000 ∨ ST_seg_ele(k1) < 1000)
            ∧
            (Abnormal_Shaped_ST(l1) = FALSE ∨ Abnormal_Shaped_ST(k1) = FALSE)))
            ⇒ l1 ≠ k1))
    grd10 : Asy_T_Inversion_strain(V5) = TRUE ∧
            Asy_T_Inversion_strain(V6) = TRUE ∧
            Asy_T_Inversion_strain(V4) = TRUE
    grd11 : Heart_State = KO
    grd12 : T_Normal_Status = FALSE
    grd13 : Axis_Devi = LAD ∧
            minAngle = -30 ∧
            maxAngle = -90

    then
        act1 : Disease_step6 := LVH_cause
    end

    Event RVH_Assessment ≐
    RVH_Assessment

    extends RVH_Assessment

    any
        age    age of men or women
        aixs   axis for deviation

    where
        grd1 : P_Wave_Peak(II) ≥ 3000
        grd2 : P_Wave_Peak(V1) ≥ 3000
        grd3 : Disease_step6 = RAE
        grd4 : R_Depth(V1) ≥ 7000 ∧ age > 30
            1 assessment
        grd5 : S_Depth(V5) ≥ 7000 ∨
            S_Depth(V6) ≥ 7000
            2 assessment

```



```

grd6 : R.S_Ratio(V1) ≥ 100
      R_S Ratio is multiply by 100 to remove the real no. constants... 3 assessment
grd7 : R.S_Ratio(V5) ≤ 100
      ∨
      R.S_Ratio(V6) ≤ 100
      4 assessment
grd8 : aixs ∈ 0 .. 360 ∧ aixs ≥ 110
      5 assessment
grd9 : Disease_step2 ∉ {LBBB, RBBB}
grd10 : QRS_Int < 120
grd11 : (∀t·t ∈ LEADS ⇒ ST_elevation(t) = TRUE
      ∨
      Q_Normal_Status = FALSE))

AorB : fromstep8development
      ∨
      (∀l1, k1·l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
      ((ST_elevation(l1) = FALSE ∨ ST_elevation(k1) = FALSE))
      ∨
      ((ST_seg_ele(l1) < 1000 ∨ ST_seg_ele(k1) < 1000)
      ∧
      (Abnormal_Shaped_ST(l1) = FALSE ∨ Abnormal_Shaped_ST(k1) = FALSE)))
      ⇒ l1 ≠ k1))
grd13 : Asy_T_Inversion_strain(V1) = TRUE ∧
      Asy_T_Inversion_strain(V2) = TRUE ∧
      Asy_T_Inversion_strain(V3) = TRUE
grd14 : Heart_State = KO
grd15 : T_Normal_Status = FALSE
grd16 : Axis_Devi = RAD ∧
      minAngle = 110 ∧
      maxAngle = 180

then
  act1 : Disease_step6 := RVH
end

Event T_Wave_Assessment_Peaked_V123456 ≐
T Wave Assessment

extends T_Wave_Assessment_Peaked_V123456

when
  grd1 : ∀l·l ∈ {V1, V2, V3, V4, V5, V6} ⇒ T.Wave_State(l) = Peaked
  grd2 : MC_Step10_Test_Needed = TRUE
  grd3 : Heart_State = KO

then
  act1 : Disease_step8 := Hyperkalemia
end

Event T_Wave_Assessment_Peaked_V12 ≐
T Wave Assessment

extends T_Wave_Assessment_Peaked_V12

when
  grd1 : R_Normal_Status = FALSE

```

```

    grd2 : T_Wave_State(V1) = Peaked ∧
           T_Wave_State(V2) = Peaked
    grd3 :
      ∨
      (∀l1, k1. l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
       ((ST_elevation(l1) = FALSE ∨ ST_elevation(k1) = FALSE)
        ∨
        ((ST_seg_ele(l1) < 1000 ∨ ST_seg_ele(k1) < 1000)
         ∧
         (Abnormal_Shaped_ST(l1) = FALSE ∨ Abnormal_Shaped_ST(k1) = FALSE)))
       ⇒ l1 ≠ k1))
grd4 : ∀l. l ∈ LEADS ⇒ T_inversion(l) < 5000
      step 8 B
grd5 : T_Normal_Status = FALSE
grd6 :
      ∨
      (Axis_Devi = RAD ∧
       minAngle = 110 ∧
       maxAngle = 180)
  then
    act1 : Mice_State := normal_variant
  end

Event T_Wave_Assessment_Peaked_V12_MI ≐
  posterior MI using T wave assessment in LEADS V1 and V2

extends T_Wave_Assessment_Peaked_V12_MI

  when
    grd1 : T_Wave_State(V1) = Peaked ∧
           T_Wave_State(V2) = Peaked
    grd6 : Heart_State = KO
    grd2 :
      ∨
      (∀l1, k1. l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
       ((ST_elevation(l1) = FALSE ∨ ST_elevation(k1) = FALSE)
        ∨
        ((ST_seg_ele(l1) < 1000 ∨ ST_seg_ele(k1) < 1000)
         ∧
         (Abnormal_Shaped_ST(l1) = FALSE ∨ Abnormal_Shaped_ST(k1) = FALSE)))
       ⇒ l1 ≠ k1))
grd3 : ∀l. l ∈ LEADS ⇒ T_inversion(l) > 5000
grd4 : T_inversion_l.d(V2) = Localized ∧
       T_inversion_l.d(V3) = Localized ∧
       T_inversion_l.d(V4) = Localized ∧
       T_inversion_l.d(V5) = Localized
grd5 : T_inversion_l.d(II) = Localized ∧
       T_inversion_l.d(III) = Localized ∧
       T_inversion_l.d(aVF) = Localized
grd7 : T_Normal_Status = FALSE
  then
    act1 : Disease_step8 := posterior_MI
  end

Event T_Wave_Assessment_Flat ≐

extends T_Wave_Assessment_Flat

  when

```

```

    grd1 :  $\forall l. l \in LEADS \Rightarrow T\_Wave\_State(l) = Flat$ 
    grd4 : Heart.State = KO
    grd2 :  $\vee$ 
      ( $\forall l, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
      ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
       $\vee$ 
      ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
       $\wedge$ 
      ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ ))
       $\Rightarrow l1 \neq k1$ )
step 8 B
grd3 :  $\forall l. l \in LEADS \Rightarrow T\_inversion(l) < 5000$ 
grd5 : T.Normal.Status = FALSE
  then
    act1 : Disease_step8 := Nonspecific.ST.T.changes
    act2 : Disease_step8.B :∈ {Cardiomyopathy, Electrolyte_depletion, Alcohol, Myocarditis, Other}
  end
Event T.Wave.Assessment.Inverted.Yes  $\hat{=}$ 
extends T.Wave.Assessment.Inverted.Yes
  when
    grd1 :  $\forall l. l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$ 
    grd2 :  $\forall l. l \in LEADS \Rightarrow ST\_elevation(l) = TRUE$ 
       $\vee$ 
      Q.Normal.Status = FALSE
    grd3 : Heart.State = KO
  then
    act1 : Disease_step8 :∈ {Definite_ischemia, Probable_ischemia, Digitalis_effect}
  end
Event T.Wave.Assessment.Inverted.No  $\hat{=}$ 
extends T.Wave.Assessment.Inverted.No
  when
    grd1 :  $\forall l. l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$ 
    grd2 :  $\forall l. l \in LEADS \Rightarrow ST\_elevation(l) = FALSE$ 
       $\vee$ 
      Q.Normal.Status = TRUE
    grd3 : Heart.State = KO
  then
    act1 : Disease_step8 := Nonspecific
  end
Event T.Wave.Assessment.Inverted.Yes.PM  $\hat{=}$ 
  PM - pulmonary embolism this disease is already defined in previous development.
extends T.Wave.Assessment.Inverted.Yes.PM
  when
    grd1 : P.Wave.Peak(II)  $\geq 3000$ 
    grd2 : P.Wave.Peak(V1)  $\geq 3000$ 
    grd3 : Disease_step6 = RAE

```

```

    grd4 :      (∀t.t ∈ LEADS ⇒ ST_elevation(t) = TRUE
                ∨
                Q_Normal_Status = FALSE))

A : step8
  ¬(∃l,k.l ∈ LEADS ∧ k ∈ LEADS ∧
    ((ST_seg_ele(l) ≥ 1000 ∧ ST_seg_ele(k) ≥ 1000) ∨
    (ST_elevation(l) = TRUE ∧ ST_elevation(k) = TRUE))
    ∨
    (Abnormal_Shaped_ST(l) = TRUE ∧ Abnormal_Shaped_ST(k) = TRUE))
    ⇒
    l ≠ k))

grd5 : Asy_T_Inversion_strain(V1) = TRUE ∧
      Asy_T_Inversion_strain(V2) = TRUE ∧
      Asy_T_Inversion_strain(V3) = TRUE

grd6 : Axis_Devi = RAD ∧
      minAngle = 110 ∧
      maxAngle = 180

grd7 : MC_Step10_Test_Needed = TRUE

grd8 : Heart_State = K0

    then

      act1 : Disease_step6 := pulmonary_embolism

    end

Event T_Wave_Assessment_B ≐
  B for alternate method of T wave assessment

extends T_Wave_Assessment_B

    when

      grd1 : ∀l.l ∈ {I, II, V3, V4, V5, V6} ⇒ T_Wave_State_B(l) = Upright
      grd2 : T_Wave_State_B(aVL) = Inverted_B
      grd3 : ∀l.l ∈ {III, aVL, aVF, V1, V2} ⇒ T_Wave_State_B(l) = Variable

    then

      act1 : T_Normal_Status := TRUE

    end

Event T_Wave_Assessment_B_DI ≐
  abnormal T wave .....in B ...DI(Definite Ischemia)

extends T_Wave_Assessment_B_DI

    when

      grd1 : ∀l.l ∈ LEADS ⇒ T_Wave_State(l) = Inverted
      grd2 : ∀l.l ∈ LEADS ⇒ ST_elevation(l) = TRUE
                ∨
                Q_Normal_Status = FALSE
      grd3 : T_Normal_Status = FALSE
                added in step-8 B
      grd5 : Heart_State = K0
      grd4 : ∃l,k.l ∈ LEADS ∧ k ∈ LEADS ∧
                ((ST_seg_ele(l) ≥ 1000 ∧ ST_seg_ele(k) ≥ 1000) ∨
                (ST_elevation(l) = TRUE ∧ ST_elevation(k) = TRUE))
                ∨
                (Abnormal_Shaped_ST(l) = TRUE ∧ Abnormal_Shaped_ST(k) = TRUE))
    
```

```

       $\wedge$ 
       $l \neq k$ 
      added in step-8 B
  then
    act1 : Disease_step8 := Definite_ischemia
  end

Event T_Inversion_Likely_Ischemia  $\hat{=}$ 
  probable Ischemia or Likly ischemia

extends T_Inversion_Likely_Ischemia

  when

    grd1 :  $\forall l. l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$ 
    grd2 :  $\forall l. l \in LEADS \Rightarrow ST\_elevation(l) = TRUE$ 
            $\vee$ 
            $Q\_Normal\_Status = FALSE$ 
    grd3 :  $\forall l. l \in LEADS \Rightarrow T\_inversion(l) > 5000$ 
            $1\text{ mm} = 1000$ 
    grd4 :  $\vee$ 
           ( $\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
            ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
             $\vee$ 
            ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
             $\wedge$ 
            ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ )))
             $\Rightarrow l1 \neq k1$ )
    grd5 :  $T\_inversion\_l.d(V2) = Localized \wedge$ 
            $T\_inversion\_l.d(V3) = Localized \wedge$ 
            $T\_inversion\_l.d(V4) = Localized \wedge$ 
            $T\_inversion\_l.d(V5) = Localized$ 
    grd6 :  $T\_inversion\_l.d(II) = Localized \wedge$ 
            $T\_inversion\_l.d(III) = Localized \wedge$ 
            $T\_inversion\_l.d(aVF) = Localized$ 
           b. of Deep inversion  $i$  5mm
    grd7 : Heart_State = K0
    grd8 :  $T\_Normal\_Status = FALSE$ 

    then
      act1 : Disease_step8 := Probable_ischemia
    end

Event T_Inversion_Diffuse_B  $\hat{=}$ 
  Step 8 B for c.

extends T_Inversion_Diffuse_B

  when

    grd1 :  $\vee$ 
           ( $\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
            ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
             $\vee$ 
            ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
             $\wedge$ 
            ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ )))
             $\Rightarrow l1 \neq k1$ )
    grd2 :  $\forall l. l \in LEADS \Rightarrow T\_inversion(l) > 5000$ 

```

```

grd3 :  $\forall l. l \in \text{LEADS} \Rightarrow \text{T.inversion.l.d}(l) = \text{Diffuse}$ 
grd4 : Heart.State = KO
grd5 : T.Normal.Status = FALSE
  then
    act1 : Disease_step8_B : $\in$  {Cardiomyopathy, other_nonspecific}
  end
Event Axis_Assessment_QRS_upright_Yes_Age_less_40  $\hat{=}$ 
extends Axis_Assessment_QRS_upright_Yes_Age_less_40
  any
    age
  where
    grd1 : QRS_Axis_State(I) = D.Upright  $\wedge$ 
           QRS_Axis_State(aVF) = D.Upright
    grd2 : age  $\in$   $\mathbb{N} \wedge$  age < 40
  then
    act1 : minAngle := 0
    act2 : maxAngle := 110
  end
Event Axis_Assessment_QRS_upright_Yes_Age_gre_40  $\hat{=}$ 
extends Axis_Assessment_QRS_upright_Yes_Age_gre_40
  any
    age
  where
    grd1 : QRS_Axis_State(I) = D.Upright  $\wedge$ 
           QRS_Axis_State(aVF) = D.Upright
    grd2 : age  $\in$   $\mathbb{N} \wedge$  age > 40
  then
    act1 : minAngle := -30
    act2 : maxAngle := 90
  end
Event Axis_Assessment_QRS_upright_No_QRS_positive  $\hat{=}$ 
extends Axis_Assessment_QRS_upright_No_QRS_positive
  when
    grd1 :  $\neg(\text{QRS\_Axis\_State}(I) = \text{D.Upright} \wedge$ 
            $\text{QRS\_Axis\_State}(aVF) = \text{D.Upright})$ 
    grd2 : QRS_Axis_State(I) = D.Positive  $\wedge$ 
           QRS_Axis_State(aVF) = D.Positive
    grd3 : Heart.State = KO
  then
    act1 : minAngle := -30
    act2 : maxAngle := -90
    act3 : Axis_Devi := LAD
  end
end

```

Event *Axis_Assessment_QRS_upright_No_QRS_negative* $\hat{=}$

extends *Axis_Assessment_QRS_upright_No_QRS_negative*

when

grd1 : $\neg(\text{QRS_Axis_State}(I) = \text{D.Upright} \wedge$
 $\text{QRS_Axis_State}(aVF) = \text{D.Upright})$
grd2 : $\text{QRS_Axis_State}(I) = \text{D.Negative} \wedge$
 $\text{QRS_Axis_State}(aVF) = \text{D.Negative}$
grd3 : $\text{Heart_State} = \text{KO}$

then

act1 : $\text{minAngle} := 110$
act2 : $\text{maxAngle} := 180$
act3 : $\text{Axis_Devi} := \text{RAD}$

end

Event *Misc_Disease_Step9_LAD* $\hat{=}$

extends *Misc_Disease_Step9_LAD*

when

grd1 : $\text{Axis_Devi} = \text{LAD} \wedge$
 $\text{minAngle} = -30 \wedge$
 $\text{maxAngle} = -90$
grd2 : $\text{Heart_State} = \text{KO}$

then

act1 : $\text{Disease_step9} \in \{\text{LAFB}, \text{MSCHD}, \text{Some_Form_VT}, \text{ED_OC}\}$

end

Event *Misc_Disease_Step9_RAD* $\hat{=}$

extends *Misc_Disease_Step9_RAD*

when

grd1 : $\text{Axis_Devi} = \text{RAD} \wedge$
 $\text{minAngle} = 110 \wedge$
 $\text{maxAngle} = 180$
grd2 : $\text{Heart_State} = \text{KO}$

then

act1 : $\text{Disease_step9} \in \{\text{LPFB}, \text{NV_MSEC}\}$

end

Event *R_Q_Assessment_R_Abnormal_V56_axis_deviation* $\hat{=}$

extends *R_Q_Assessment_R_Abnormal_V56_axis_deviation*

when

grd1 : $\text{Q_Wave_State}(V5) = \text{TRUE} \wedge$
 $\text{Q_Wave_State}(V6) = \text{TRUE}$
grd2 : $\text{Axis_Devi} = \text{RAD} \wedge$
 $\text{minAngle} = 110 \wedge$
 $\text{maxAngle} = 180$
grd3 : $\text{Heart_State} = \text{KO}$

then

act1 : $\text{Disease_step5} := \text{lateral_MI}$

```

    end
Event Miscellaneous_Conditions_Step10 ≐
extends Miscellaneous_Conditions_Step10
    when
        grd1 : MC.Step10.Test_Needed = TRUE
        grd2 : Heart_State = KO
    then
        act1 : Disease_step10 := {Incomplete_RBBB, Pericarditis, Long_QT, Hypokalemia,
            Digitalis_toxicity, Electrical_alternans, Electronic_pacing, Hypothermia, Hypercalcemia}
    end
Event Misc_Disease_Step10_Dextrcardia_Test ≐
extends Misc_Disease_Step10_Dextrcardia_Test
    when
        grd1 : Axis_Devi = RAD ∧
            minAngle = 110 ∧
            maxAngle = 180
        grd2 : MC.Step10.Test_Needed = TRUE
        grd3 : Heart_State = KO
    then
        act1 : Disease_step9 := Dextrocardia
    end
Event Rhythm_test_FALSE_Step11 ≐
extends Rhythm_test_FALSE
    any
        rate
    where
        grd1 : (∀l. l ∈ {II, V1, V2} ⇒ PP_Int_equidistant(l) = FALSE ∨
            RR_Int_equidistant(l) = FALSE ∨
            RR_Interval(l) ≠ PP_Interval(l))
            ∨
            P_Positive(II) = FALSE
        grd2 : rate ∈ 1 .. 300
        grd5 : rate ∈ 1 .. 300
    then
        act1 : Sinus := No
        act2 : Heart_Rate := rate
        act3 : Heart_State := KO
        act4 : Disease_step11 := {Atrial_Premature_Beats, Ventricular_Premature_Beats,
            Nodal_Premature_Beats, Bradyarrhythmias, Narrow_QRS_Tachycardias, Wide_QRS_Tachycardias}
    end
end
END

```


An Event-B Specification of Step11_Abnormal_Rhythm_Ref1
Generated Date: 25 Nov 2010 @ 03:39:53 PM

MACHINE Step11_Abnormal_Rhythm_Ref1

REFINES Step_11_Abnormal_Rhythm

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx, Step8_ctx, Step9, Step10_ctx, Step11_ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
Small_R_QS A small R or QS wave in V1 and V2
Slurred_S_duration Slurred S duration
Delta_Wave Delta Wave
Disease_step3
ST_elevation ST segment elevation (Coved or Saddle-back)
Epsilon_Wave Epsilon Wave or (a terminal notch in the QRS)
ST_seg_ele ST segment for elevation 1mm=0.1mV
Disease_step4
Q_Width Q wave width
Q_Depth Q wave depth
Q_Normal_Status Q wave normal or abnormal
Age_of_Inf Age of Infarct
Disease_step5
Mice_State
R_Depth R wave depth or height (also use in Step 7)
R_Normal_Status R wave normal or abnormal
Q_Wave_State Q wave states for all LEADS
P_Wave_Peak function to estimate the peak of LEADS signal
Disease_step6
PP_Interval
RR_Interval
Diphasic
P_Wave_Broad

S_Depth S wave depth or height
 R_S_Ratio R wave and S wave Ratio function
 T_Wave_State T wave patterns...
 Disease_step8
 T_Wave_State_B B for alternative method of T wave assessment
 T_Normal_Status T wave normal or abnormal
 Abnormal_Shaped_ST
 Asy_T_Inversion_strain Asymmetric T wave Inversion strain pattern
 T_inversion Deep T wave inversion
 T_inversion_l_d T inversion Localized and Diffuse
 Disease_step8_B
 QRS_Axis_State QRS Axis Direction
 minAngle min. value of angle of Axis in degree
 maxAngle max. value of angle of Axis in degree
 Axis_Devi Axis Deviation in LEADS...
 Disease_step9
 Disease_step10
 MC_Step10_Test_Needed Miscellaneous Conditions test in Step 10
 Disease_step11
 Distease_step11_NW_QRST
 ST_depression

INVARIANTS

inv1 : $Distease_step11_NW_QRST \in Disease_Codes_Step11_NW_QRS_T$

inv2 : $Sinus = Yes \wedge Distease_step11_NW_QRST \in \{Ventricular_Tachycardia, Supraventricular_Tachycardia, AVNRT, WPW_Syndrome_Orthodromic, Sinus_Tachycardia, Atrial_Tachycardia, AF_Fixed_AV_Conduction, WPW_Syndrome_Antidromic, AF_BBB_WPW_Synd_Antidromic, AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti, Torsades_de_pointes\}$
 $\Rightarrow Heart_State = KO$

inv3 : $Sinus = Yes \wedge Distease_step11_NW_QRST \in \{Sinus_Tachycardia, AVNRT, AF_Fixed_AV_Conduction, AT_Paroxysmal_NParoxysmal, WPW_Syndrome_OCMT, Atrial_Fibrillation, AF_Variable_AV_Conduction, AT_Variable_AV_Block, Multifocal_Atrial_Tachycardia\}$
 $\Rightarrow Heart_State = KO$

EVENTS

Initialisation

extended

begin

act1 : $RR_Int_equidistant \in LEADS \rightarrow BOOL$
act2 : $PP_Int_equidistant \in LEADS \rightarrow BOOL$
act3 : $P_Positive \in LEADS \rightarrow BOOL$
act4 : $Sinus := No$
act5 : $PP_Interval \in LEADS \rightarrow \mathbb{N}$
act6 : $RR_Interval \in LEADS \rightarrow \mathbb{N}$
act7 : $Heart_Rate \in 1..300$
act8 : $Heart_State := KO$
act9 : $PR_Int := 120$

```

act10 : Disease_step2 := NDS2
act11 : QRS_Int := 50
act12 : Notched_R :∈ LEADS → BOOL
act13 : Small_R_QS :∈ LEADS → BOOL
act14 : Slurred_S_duration :∈ LEADS → ℕ1
act15 : M_Shape_Complex :∈ LEADS → BOOL
act16 : Slurred_S :∈ LEADS → BOOL
act17 : ST_elevation :∈ LEADS → BOOL
act18 : Epsilon_Wave :∈ LEADS → BOOL
act19 : Delta_Wave := 0
act20 : Disease_step3 := NDS3
act21 : ST_seg_ele :∈ LEADS → ℕ
act22 : Disease_step4 := NDS4
act57 : ST_depression :∈ LEADS → ℕ
act23 : Q_Width :∈ LEADS → ℕ
act24 : Q_Depth :∈ LEADS → ℕ
act25 : Q_Normal_Status := FALSE
act26 : Mice_State := NMS
act27 : R_Depth :∈ LEADS → ℕ
act28 : R_Normal_Status := FALSE
act29 : Q_Wave_State :∈ LEADS → BOOL
act30 : Age_of_Inf :∈ Age_of_Infarct
act31 : Disease_step5 := NDS5
act32 : Diphasic :∈ LEADS → BOOL
act33 : P_Wave_Broad :∈ LEADS → ℕ
act34 : P_Wave_Peak :∈ LEADS → ℕ
act35 : Disease_step6 := NDS6
act36 : S_Depth :∈ LEADS → ℕ
act37 : R_S_Ratio :∈ LEADS → ℕ
act38 : T_Wave_State :∈ LEADS → T_State
act39 : Disease_step8 := NDS8
act40 : Abnormal_Shaped_ST :∈ LEADS → BOOL
act41 : Asy_T_Inversion_strain :∈ LEADS → BOOL
act43 : T_inversion_l.d :∈ LEADS → T_State_l.d
act42 : T_inversion :∈ LEADS → ℕ
act44 : Disease_step8_B := NDS8B
act45 : T_Wave_State_B :∈ LEADS → T_State_B
act46 : T_Normal_Status := FALSE
act47 : QRS_Axis_State :∈ LEADS → QRS_directions
act48 : minAngle := 0
act49 : maxAngle := 0
act50 : Axis_Devi := ND
act51 : Disease_step9 := NDS9
act52 : Disease_step10 := NDS10
act53 : MC_Step10_Test_Needed := FALSE
act54 : Disease_step11 := NDS11
act55 : Disease_step11_NW_QRST := NDS11_NW_QRS

```

end

Event *Rhythm_test_TRUE* $\hat{=}$
Sinus Rhythm with Normal Rate

```

extends Rhythm_test_TRUE

  any
    rate
  where
    grd1 : ( $\exists l. l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
       $RR\_Int\_equidistant(l) = TRUE \wedge$ 
       $RR\_Interval(l) = PP\_Interval(l)$ 
       $\wedge$ 
       $P\_Positive(II) = TRUE$ )
    grd4 : rate  $\in 60..100$ 
      60..100 is the range of normal heart rate
    grd5 : PR.Int  $\leq 200$ 
      Heart is Normal if PR  $\leq 200$  QRS.Int  $< 120$ 
      HeartisNormalifQRS  $< 120$ 
    grd6 : Disease_step2 = NDS2
    grd7 : Disease_step3 = NDS3
    grd8 : Disease_step4 = NDS4
    grd9 : Disease_step5 = NDS5
    grd10 : Disease_step6 = NDS6
    grd11 : Disease_step8 = NDS8
    grd12 : Disease_step8_B = NDS8B
    grd13 : Disease_step9 = NDS9
    grd14 : Disease_step10 = NDS10
    grd15 : Disease_step11 = NDS11
    grd16 : Disease_step11_NW_QRST = NDS11_NW_QRS
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := OK
  end

Event Rhythm_test_FALSE  $\hat{=}$ 
  Abnormal Rhythm with Rate

extends Rhythm_test_FALSE

  any
    rate
  where
    grd1 : ( $\forall l. l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \vee$ 
       $RR\_Int\_equidistant(l) = FALSE \vee$ 
       $RR\_Interval(l) \neq PP\_Interval(l)$ 
       $\vee$ 
       $P\_Positive(II) = FALSE$ )
    grd2 : rate  $\in 1..300$ 
  then
    act1 : Sinus := No
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end

```

Event *Rhythm_test.TRUE_Rate* $\hat{=}$
Sinus Rhythm with abnormal Rate

extends *Rhythm_test.TRUE_Rate*

any

rate

where

grd1 : $(\exists l. l \in \{II, V1, V2\} \wedge PP_Int_equidistant(l) = TRUE \wedge$
RR_Int_equidistant(l) = TRUE \wedge
RR_Interval(l) = PP_Interval(l))
 \wedge
P_Positive(II) = TRUE

grd5 : rate $\in 1..300 \setminus 60..100$

60..100 is the range of normal heart rate, so rest of no. is abnormal

grd6 : Disease_step3 = WPW_Syndrome \vee Disease_step3 = Brugada_Syndrome \vee
Disease_step3 = RV_Dysplasia \vee Disease_step3 = IVCD

then

act1 : Sinus := Yes

act2 : Heart_Rate := rate

act3 : Heart_State := KO

end

Event *PR_Test* $\hat{=}$
PR Interval Test

extends *PR_Test*

any

pr

where

grd1 : pr $\in 120..220$
time interval in (ms.)

grd2 : pr > 200

grd3 : Sinus = Yes

grd4 : Heart_State = KO

then

act1 : PR_Int := pr

act2 : Disease_step2 := First_degree_AV_Block

end

Event *QRS_Test_LBBB* $\hat{=}$
QRS Complex Interval Test

extends *QRS_Test_LBBB*

any

qrs

where

grd1 : qrs $\in 50..150$

grd2 : qrs ≥ 120

grd3 : Sinus = Yes

grd4 : Heart_State = KO

```

    grd5 : Notched_R(I) = TRUE ∧
           Notched_R(V5) = TRUE ∧
           Notched_R(V6) = TRUE
           Right Bundle Branch Block (RBBB)
    grd6 : Small_R_QS(V1) = TRUE ∧
           Small_R_QS(V2) = TRUE
    grd7 : Q_Wave_State(V1) = TRUE ∧
           Q_Wave_State(V2) = TRUE ∧
           Q_Wave_State(V3) = TRUE ∧
           Q_Wave_State(V4) = TRUE
           from step 5
    grd8 : R_Normal_Status = FALSE
           from step 5
    grd9 : Axis_Devi = LAD ∧
           minAngle = -30 ∧
           maxAngle = -90

  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := LBBB
  end

Event QRS_Test_RBBB ≐
  Right Bundle Branch Block (RBBB)

extends QRS_Test_RBBB

any
  qrs
where
  grd1 : qrs ∈ 50 .. 150
  grd2 : qrs ≥ 120
  grd3 : Sinus = Yes
  grd4 : Heart_State = KO
  grd5 : M_Shape_Complex(V1) = TRUE ∧
           M_Shape_Complex(V2) = TRUE
  grd7 : Slurred_S(I) = TRUE ∧
           Slurred_S(V5) = TRUE ∧
           Slurred_S(V6) = TRUE
  grd8 : Slurred_S_duration(I) > 40 ∧
           Slurred_S_duration(V5) > 40 ∧
           Slurred_S_duration(V6) > 40

  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := RBBB
  end

end

Event QRS_Test_Atypical_RLBBB_WPW_Syndrome ≐
  QRS Test for Atypical LBBB RBBB

extends QRS_Test_Atypical_RLBBB_WPW_Syndrome

any
  sympt
  d_wave

```

```

    exmi
where
    grd1 : QRS_Int ≥ 110
    grd2 : sympt = A_RBBB ∨ sympt = A_LBBB
    grd3 : d_wave ∈ ℕ
    grd4 : (d_wave + PR_Int) ≤ 120
           Delta_Wave + PR ≤ 120 Heart_State = KO
    grd5 : Disease_step4 = Acute_inferior_MI
    grd6 : Disease_step4 = Acute_inferior_MI
    grd7 : exmi ∈ Mice_State5 ∧ exmi = Exclude_Mimics_MI
then
    act2 : Delta_Wave := d_wave
    act3 : Disease_step3 := WPW_Syndrome
end

Event QRS_Test_Atypical_RBBB_Brugada_Syndrome ≐
    Atypical_RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends QRS_Test_Atypical_RBBB_Brugada_Syndrome

any
    sympt
    dis
where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int ≥ 110
    grd4 : Slurred_S(V5) = FALSE ∧
           Slurred_S(V6) = FALSE
    grd5 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, NDS3}
    grd6 : ST_elevation(V1) = TRUE ∧
           ST_elevation(V2) = TRUE
    grd7 : Sinus = Yes
then
    act1 : Disease_step3 := Brugada_Syndrome
end

Event QRS_Test_Atypical_RBBB_RV_Dysplasia ≐
    Right_Ventricular_Dysplasia

extends QRS_Test_Atypical_RBBB_RV_Dysplasia

any
    sympt
    dis
where
    grd1 : sympt = A_RBBB
    grd2 : Heart_State = KO
    grd3 : QRS_Int ≥ 110
    grd4 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, NDS3}
    grd5 : Epsilon_Wave(V1) = TRUE ∧
           Epsilon_Wave(V3) = TRUE
then

```

```

        act1 : Disease_step3 := RV_Dysplasia
    end
Event QRS_Test_Atypical_RBBB_IVCD  $\hat{=}$ 
    IVCD diagnosis
extends QRS_Test_Atypical_RBBB_IVCD
    any
        dis
    where
        grd1 : QRS_Int  $\geq$  110
        grd2 : dis  $\in$  Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, NDS3}
        grd3 : Heart_State = KO
    then
        act1 : Disease_step3 := IVCD
    end
Event ST_seg_elevation_YES  $\hat{=}$ 
    ST segment elevation...
extends ST_seg_elevation_YES
    when
        grd1 : Heart_State = KO
        grd2 : Sinus = Yes
        grd3 :
             $\vee$ 
            (( $\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
            (ST_elevation(l1) = TRUE  $\wedge$  ST_elevation(k1) = TRUE)
             $\wedge$ 
            (ST_seg_ele(l1)  $\geq$  1000  $\wedge$  ST_seg_ele(k1)  $\geq$  1000)
             $\wedge$  l1  $\neq$  k1
             $\wedge$ 
            (
            (l1 = V1  $\wedge$  k1 = V2)  $\vee$ 
            (l1 = V2  $\wedge$  k1 = V3)  $\vee$ 
            (l1 = V3  $\wedge$  k1 = V4)  $\vee$ 
            (l1 = V4  $\wedge$  k1 = V5)  $\vee$ 
            (l1 = V5  $\wedge$  k1 = V6)
            )
            ))
        grd4 : Disease_step4  $\in$  {Acute_inferior_MI, Acute_anterior_MI}
    then
        act1 : Disease_step4 := STEMI
    end
Event ST_seg_elevation_NOTCKMB_Yes  $\hat{=}$ 
    Troponin or CK-MB positive YES
extends ST_seg_elevation_NOTCKMB_Yes
    when
        grd1 : Heart_State = KO
        grd2 : Sinus = Yes

```



```

    grd3 :  $\vee$ 
      ( $\forall l \cdot l1 \in \{II, III, aVF\} \Rightarrow$ 
        ( $ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000$ ))
grd4 :  $\exists l, k \cdot l \in LEADS \wedge k \in LEADS \wedge$ 
      ( $ST\_depression(l) \geq 1000 \wedge ST\_depression(k) \geq 1000$ 
         $\wedge l \neq k$ )
grd5 : Disease_step4  $\in$  {Troponin, CK_MB}
  then
    act1 : Disease_step4 := Non_STEMI
  end

Event ST_seg_elevation_NO_TCKMB_No  $\hat{=}$ 
  Troponin or CK-MB positive No

extends ST_seg_elevation_NO_TCKMB_No

  when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :  $\vee$ 
      ( $\forall l \cdot l1 \in \{II, III, aVF\} \Rightarrow$ 
        ( $ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000$ ))
grd4 :  $\exists l, k \cdot l \in LEADS \wedge k \in LEADS \wedge$ 
      ( $ST\_depression(l) \geq 1000 \wedge ST\_depression(k) \geq 1000$ 
         $\wedge l \neq k$ )
grd5 : Disease_step4  $\notin$  {Troponin, CK_MB}
grd6 :  $\forall l \cdot l \in LEADS \Rightarrow T\_inversion(l) < 5000$ 
grd7 : T_Normal_Status = FALSE
  then
    act1 : Disease_step4 := Ischemia
  end

Event Q_Assessment_Normal  $\hat{=}$ 
  Q wave assessment normal

extends Q_Assessment_Normal

  when
    grd1 : Q_Width(II) < 40  $\wedge$  Q_Depth(II)  $\leq$  3000  $\wedge$ 
      Q_Width(aVF) < 40  $\wedge$  Q_Depth(aVF)  $\leq$  3000  $\wedge$ 
      Q_Width(aVL) < 40
      1000 micrometer = 1 millimeter
    grd2 : Q_Width(III)  $\leq$  40  $\wedge$  Q_Depth(III)  $\leq$  7000  $\wedge$  Q_Depth(aVL)  $\leq$  7000
    grd3 : Q_Depth(I) < 40  $\wedge$  Q_Depth(I)  $\leq$  1500
  then
    act1 : Q_Normal_Status := TRUE
  end

Event Q_Assessment_Abnormal_AMI  $\hat{=}$ 
  Q wave assessment abnormal for anterolateral MI (AMI)

extends Q_Assessment_Abnormal_AMI

  when
    grd1 : Heart_State = KO

```

```

    grd2 : Sinus = Yes
    grd3 :          ∨
    ((∃l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
    (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
    ∧
    (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
    ∧ l1 ≠ k1
    ∧
    (
    (l1 = V1 ∧ k1 = V2) ∨
    (l1 = V2 ∧ k1 = V3) ∨
    (l1 = V3 ∧ k1 = V4) ∨
    (l1 = V4 ∧ k1 = V5) ∨
    (l1 = V5 ∧ k1 = V6)
    )
    ))
grd4 : Q_Width(V5) ≥ 40 ∧ Q_Depth(V5) > 3000 ∧
      Q_Width(V6) ≥ 40 ∧ Q_Depth(V6) > 3000
grd5 : Q_Width(aVL) ≥ 40 ∧ Q_Depth(aVL) > 7000
grd6 : Q_Depth(I) ≥ 40 ∧ Q_Depth(I) > 1500
grd7 : Q_Normal_Status = FALSE
  then
    act1 : Disease_step4 := Acute_anterior_MI
  end

Event Q_Assessment_Abnormal_IMI ≐
  Q_wave_assessment_abnormal_for_inferior_MI (IMI)

extends Q_Assessment_Abnormal_IMI

  when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :          ∨
    ((∃l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
    (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
    ∧
    (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
    ∧ l1 ≠ k1
    ∧
    (
    (l1 = V1 ∧ k1 = V2) ∨
    (l1 = V2 ∧ k1 = V3) ∨
    (l1 = V3 ∧ k1 = V4) ∨
    (l1 = V4 ∧ k1 = V5) ∨
    (l1 = V5 ∧ k1 = V6)
    )
    ))
grd4 : Q_Width(II) ≥ 40 ∧ Q_Depth(II) > 3000 ∧
      Q_Width(III) > 40 ∧ Q_Depth(III) > 7000 ∧
      Q_Width(aVF) ≥ 40 ∧ Q_Depth(aVF) > 3000
grd5 : Q_Normal_Status = FALSE
  then
    act1 : Disease_step4 := Acute_inferior_MI
  end

```

```

Event Determine_Age_of_Infarct  $\hat{=}$ 
extends Determine_Age_of_Infarct
  when
    grd1 : Disease_step4 = Acute_inferior_MI
           $\vee$ 
          Disease_step5  $\in$  {anterior_MI, LVH, emphysema}
           $\vee$ 
          Mice_State = Exclude_Mimics_MI
           $\vee$ 
          Disease_step2 = LBBB
  then
    act1 : Age_of_Inf  $:\in$  {recent, old, indeterminate}
  end

Event Exclude_Mimics  $\hat{=}$ 
extends Exclude_Mimics
  any
    exmi
  where
    grd1 : Disease_step4 = Acute_inferior_MI
    grd2 : exmi  $\in$  Mice_State5  $\wedge$  exmi = Exclude_Mimics_MI
  then
    act1 : Disease_step5 := Hypertrophic_cardiomyopathy
    act2 : Mice_State := borderline_Qs
  end

Event R_Assessment_Normal  $\hat{=}$ 
  Q wave assessment normal
extends R_Assessment_Normal
  any
    age
  where
    grd1 : R.Depth(V1)  $\geq$  0  $\wedge$  R.Depth(V1)  $\leq$  6000  $\wedge$  age > 30
           1000 micrometer = 1 millimeter
    grd2 : R.Depth(V2) > 200  $\wedge$  R.Depth(V2)  $\leq$  12000
    grd3 : R.Depth(V2)  $\geq$  1000  $\wedge$  R.Depth(V2)  $\leq$  24000
  then
    act1 : R.Normal_Status := TRUE
  end

Event R_Assessment_Abnormal  $\hat{=}$ 
extends R_Assessment_Abnormal
  when
    grd1 : R.Normal_Status = FALSE
  then
    act1 : Mice_State  $:\in$  {late_transition, normal_variant}

```

```

end

Event R_Q_Assessment_R_Abnormal_V1234 ≐
  R wave abnormal , pathologic Q waves consider in V1-V4

extends R_Q_Assessment_R_Abnormal_V1234

when
  grd1 : R.Normal_Status = FALSE
  grd2 : Q_Wave_State(V1) = TRUE ∧
        Q_Wave_State(V2) = TRUE ∧
        Q_Wave_State(V3) = TRUE ∧
        Q_Wave_State(V4) = TRUE
  grd3 : Heart_State = KO
then
  act1 : Disease_step5 ∈ {anterior_MI, LVH, emphysema}
  act2 : Mice_State := Exclude_Mimics_MI
end

Event R_Q_Assessment_R_Abnormal_V56 ≐
  R wave abnormal , pathologic Q waves consider in V5-V6

extends R_Q_Assessment_R_Abnormal_V56

when
  grd1 : Q_Wave_State(V5) = TRUE ∧
        Q_Wave_State(V6) = TRUE
  grd2 : Heart_State = KO
then
  act1 : Disease_step5 := Hypertrophic_cardiomyopathy
end

Event P_Wave_assessment_Peaked_Broad_No ≐

extends P_Wave_assessment_Peaked_Broad_No

when
  grd1 : (P_Wave_Peak(II) < 3000 ∧
        P_Wave_Peak(V1) < 3000)
        ∨
        (P_Wave_Broad(II) < 110 ∧ P_Wave_Broad(V1) < 110) ∨
        Diphasic(II) = FALSE ∨
        Diphasic(V1) = FALSE
then
  act1 : Disease_step6 := NDS6
end

Event P_Wave_assessment_Peaked_Yes ≐

extends P_Wave_assessment_Peaked_Yes

when
  grd1 : P_Wave_Peak(II) ≥ 3000
  grd2 : P_Wave_Peak(V1) ≥ 3000
  grd3 : Heart_State = KO
then

```

```

        act1 : Disease_step6 := RAE
    end
Event P_Wave_assessment_Peaked_Yes_Check_RAE  $\hat{=}$ 
extends P_Wave_assessment_Peaked_Yes_Check_RAE
    when
        grd1 : P.Wave_Peak(II)  $\geq$  3000
        grd2 : P.Wave_Peak(V1)  $\geq$  3000
        grd3 : Disease_step6 = RAE
        grd4 : Heart_State = KO
    then
        act1 : Disease_step6 := RV_strain
    end
Event P_Wave_assessment_Broad_Yes  $\hat{=}$ 
extends P_Wave_assessment_Broad_Yes
    when
        grd1 : (P.Wave_Broad(II)  $\geq$  110  $\wedge$  P.Wave_Broad(V1)  $\geq$  110)  $\vee$ 
            Diphasic(II) = TRUE  $\vee$ 
            Diphasic(V1) = TRUE
        grd2 : Heart_State = KO
    then
        act1 : Disease_step6 := LAE
    end
Event P_Wave_assessment_Broad_Yes_Check_LAE  $\hat{=}$ 
extends P_Wave_assessment_Broad_Yes_Check_LAE
    when
        grd1 : (P.Wave_Broad(II)  $\geq$  110  $\wedge$  P.Wave_Broad(V1)  $\geq$  110)  $\vee$ 
            Diphasic(II) = TRUE  $\vee$ 
            Diphasic(V1) = TRUE
        grd2 : Disease_step6 = LAE
        grd3 : Heart_State = KO
    then
        act1 : Disease_step6  $\in$  {mitral_stenosis, mitral_regurgitation, LV_failure,
            dilated_cardiomyopathy}
    end
Event LVH_Assessment  $\hat{=}$ 
    LVH_Assessment
extends LVH_Assessment
    any
        LVH_specificity    specificity in percentage
        sensitivity        sensitivity in percentage
        sex
    where

```

```

grd1 : (P_Wave_Broad(II) ≥ 110 ∧ P_Wave_Broad(V1) ≥ 110) ∨
      Diphasic(II) = TRUE ∨
      Diphasic(V1) = TRUE
grd2 : Disease_step6 = LAE
grd5 : sex ∈ {0, 1}
      o for men and 1 for women
grd3 : ((S_Depth(V1) + R_Depth(V5)) > 35000
      ∨
      (S_Depth(V1) + R_Depth(V6)) > 35000)
      1mm = 1000 micrometer..... 1 assessment
grd4 : ((R_Depth(aVL) + S_Depth(V1) ≥ 24000) ∧ sex = 0)
      ∨
      ((R_Depth(aVL) + S_Depth(V1) ≥ 18000) ∧ sex = 1)
      2 assessment
grd6 : LVH_specificity = 90
      ∧
      sensitivity < 40
      1 and 2 assessment
grd7 : Disease_step6 = LAE ⇒ LVH_specificity < 98
      3 assessment
grd8 : (∀t.t ∈ LEADS ⇒ ST_elevation(t) = TRUE
      ∨
      Q_Normal_Status = FALSE))
      A or B : from step 8 development
grd9 : ∨
      (∀l1, k1.l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
      ((ST_elevation(l1) = FALSE ∨ ST_elevation(k1) = FALSE)
      ∨
      ((ST_seg_ele(l1) < 1000 ∨ ST_seg_ele(k1) < 1000)
      ∧
      (Abnormal_Shaped_ST(l1) = FALSE ∨ Abnormal_Shaped_ST(k1) = FALSE)))
      ⇒ l1 ≠ k1))
grd10 : Asy_T_Inversion_strain(V5) = TRUE ∧
        Asy_T_Inversion_strain(V6) = TRUE ∧
        Asy_T_Inversion_strain(V4) = TRUE
grd11 : Heart_State = KO
grd12 : T_Normal_Status = FALSE
grd13 : Axis_Devi = LAD ∧
        minAngle = -30 ∧
        maxAngle = -90

then
  act1 : Disease_step6 := LVH_cause
end

Event RVH_Assessment ≐
RVH_Assessment

extends RVH_Assessment

any
  age    age of men or women
  aixs   axis for deviation

where
  grd1 : P_Wave_Peak(II) ≥ 3000

```

```

grd2 : P.Wave.Peak(V1) ≥ 3000
grd3 : Disease_step6 = RAE
grd4 : R.Depth(V1) ≥ 7000 ∧ age > 30
      1 assessment
grd5 : S.Depth(V5) ≥ 7000 ∨
      S.Depth(V6) ≥ 7000
      2 assessment
grd6 : R.S.Ratio(V1) ≥ 100
      R.S.Ratio is multiply by 100 to remove the real no. constants... 3 assessment
grd7 : R.S.Ratio(V5) ≤ 100
      ∨
      R.S.Ratio(V6) ≤ 100
      4 assessment
grd8 : aixs ∈ 0..360 ∧ aixs ≥ 110
      5 assessment
grd9 : Disease_step2 ∉ {LBBB, RBBB}
grd10 : QRS_Int < 120
grd11 : (∀t.t ∈ LEADS ⇒ ST_elevation(t) = TRUE
      ∨
      Q_Normal_Status = FALSE))

```

AorB : fromstep8development

```

∨
(∀l1, k1.l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
((ST_elevation(l1) = FALSE ∨ ST_elevation(k1) = FALSE)
∨
((ST_seg_ele(l1) < 1000 ∨ ST_seg_ele(k1) < 1000)
∧
(Abnormal_Shaped_ST(l1) = FALSE ∨ Abnormal_Shaped_ST(k1) = FALSE)))
⇒ l1 ≠ k1))

```

```

grd13 : Asy_T_Inversion_strain(V1) = TRUE ∧
Asy_T_Inversion_strain(V2) = TRUE ∧
Asy_T_Inversion_strain(V3) = TRUE

```

```

grd14 : Heart_State = KO

```

```

grd15 : T_Normal_Status = FALSE

```

```

grd16 : Axis_Devi = RAD ∧
minAngle = 110 ∧
maxAngle = 180

```

then

```

act1 : Disease_step6 := RVH

```

end

Event *T_Wave_Assessment_Peaked_V123456* ≐
T Wave Assessment

extends *T_Wave_Assessment_Peaked_V123456*

when

```

grd1 : ∀l.1 ∈ {V1, V2, V3, V4, V5, V6} ⇒ T.Wave_State(1) = Peaked
grd2 : MC_Step10_Test_Needed = TRUE
grd3 : Heart_State = KO

```

then

```

act1 : Disease_step8 := Hyperkalemia

```

end

Event *T_Wave_Assessment_Peaked_V12* $\hat{=}$

extends *T_Wave_Assessment_Peaked_V12*

when

grd1 : R.Normal_Status = FALSE

grd2 : T.Wave_State(V1) = Peaked \wedge
T.Wave_State(V2) = Peaked

grd3 : \vee

$(\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$
 $((ST_elevation(l1) = FALSE \vee ST_elevation(k1) = FALSE)$

\vee

$((ST_seg_ele(l1) < 1000 \vee ST_seg_ele(k1) < 1000)$

\wedge

$(Abnormal_Shaped_ST(l1) = FALSE \vee Abnormal_Shaped_ST(k1) = FALSE)))$

$\Rightarrow l1 \neq k1)$

grd4 : $\forall l. l \in LEADS \Rightarrow T.inversion(l) < 5000$

step 8 B

grd5 : T.Normal_Status = FALSE

grd6 : \vee

$(Axis_Devi = RAD \wedge$

$minAngle = 110 \wedge$

$maxAngle = 180)$

then

act1 : Mice_State := normal_variant

end

Event *T_Wave_Assessment_Peaked_V12_MI* $\hat{=}$

posterior MI using T wave assessment in LEADS V1 and V2

extends *T_Wave_Assessment_Peaked_V12_MI*

when

grd1 : T.Wave_State(V1) = Peaked \wedge
T.Wave_State(V2) = Peaked

grd6 : Heart_State = KO

grd2 : \vee

$(\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$

$((ST_elevation(l1) = FALSE \vee ST_elevation(k1) = FALSE)$

\vee

$((ST_seg_ele(l1) < 1000 \vee ST_seg_ele(k1) < 1000)$

\wedge

$(Abnormal_Shaped_ST(l1) = FALSE \vee Abnormal_Shaped_ST(k1) = FALSE)))$

$\Rightarrow l1 \neq k1)$

grd3 : $\forall l. l \in LEADS \Rightarrow T.inversion(l) > 5000$

grd4 : T.inversion_l.d(V2) = Localized \wedge

T.inversion_l.d(V3) = Localized \wedge

T.inversion_l.d(V4) = Localized \wedge

T.inversion_l.d(V5) = Localized

grd5 : T.inversion_l.d(II) = Localized \wedge

T.inversion_l.d(III) = Localized \wedge

T.inversion_l.d(aVF) = Localized

grd7 : T.Normal_Status = FALSE

then

act1 : Disease_step8 := posterior_MI


```

    end

Event T_Wave_Assessment_Flat  $\hat{=}$ 
extends T_Wave_Assessment_Flat

    when
        grd1 :  $\forall l \cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Flat$ 
        grd4 : Heart_State = KO
        grd2 :  $\vee$ 
            ( $\forall l, k1 \cdot l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
            ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
             $\vee$ 
            ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
             $\wedge$ 
            ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ ))
             $\Rightarrow l1 \neq k1$ )
    step 8 B
grd3 :  $\forall l \cdot l \in LEADS \Rightarrow T\_inversion(l) < 5000$ 
grd5 : T_Normal_Status = FALSE

    then
        act1 : Disease_step8 := Nonspecific_ST_T_changes
        act2 : Disease_step8_B  $\in$  {Cardiomyopathy, Electrolyte_depletion, Alcohol, Myocarditis, Other}
    end

Event T_Wave_Assessment_Inverted_Yes  $\hat{=}$ 
extends T_Wave_Assessment_Inverted_Yes

    when
        grd1 :  $\forall l \cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$ 
        grd2 :  $\forall l \cdot l \in LEADS \Rightarrow ST\_elevation(l) = TRUE$ 
             $\vee$ 
            Q_Normal_Status = FALSE
        grd3 : Heart_State = KO

    then
        act1 : Disease_step8  $\in$  {Definite_ischemia, Probable_ischemia, Digitalis_effect}
    end

Event T_Wave_Assessment_Inverted_No  $\hat{=}$ 
extends T_Wave_Assessment_Inverted_No

    when
        grd1 :  $\forall l \cdot l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$ 
        grd2 :  $\forall l \cdot l \in LEADS \Rightarrow ST\_elevation(l) = FALSE$ 
             $\vee$ 
            Q_Normal_Status = TRUE
        grd3 : Heart_State = KO

    then
        act1 : Disease_step8 := Nonspecific
    end

Event T_Wave_Assessment_Inverted_Yes_PM  $\hat{=}$ 
    PM - pulmonary embolism this disease is already defined in previous development.

```

extends *T_Wave_Assessment_Inverted_Yes_PM*

when

grd1 : P_Wave_Peak(II) ≥ 3000
grd2 : P_Wave_Peak(V1) ≥ 3000
grd3 : Disease_step6 = RAE
grd4 : $(\forall t \cdot t \in LEADS \Rightarrow ST_elevation(t) = TRUE)$
 \vee
 $(Q_Normal_Status = FALSE)$

A : step8

$\neg(\exists l, k \cdot l \in LEADS \wedge k \in LEADS \wedge$
 $((ST_seg_ele(l) \geq 1000 \wedge ST_seg_ele(k) \geq 1000) \vee$
 $(ST_elevation(l) = TRUE \wedge ST_elevation(k) = TRUE))$
 \vee
 $(Abnormal_Shaped_ST(l) = TRUE \wedge Abnormal_Shaped_ST(k) = TRUE))$
 \Rightarrow
 $l \neq k)$

grd5 : Asy_T_Inversion_strain(V1) = TRUE ∧
 Asy_T_Inversion_strain(V2) = TRUE ∧
 Asy_T_Inversion_strain(V3) = TRUE

grd7 : Axis_Devi = RAD ∧
 minAngle = 110 ∧
 maxAngle = 180

grd8 : MC_Step10_Test_Needed = TRUE

grd9 : Heart_State = K0

then

act1 : Disease_step6 := pulmonary_embolism

end

Event *T_Wave_Assessment_B* ≐

B for alternate method of T wave assessment

extends *T_Wave_Assessment_B*

when

grd1 : $\forall l \cdot l \in \{I, II, V3, V4, V5, V6\} \Rightarrow T_Wave_State_B(l) = Upright$
grd2 : T_Wave_State_B(aVL) = Inverted_B
grd3 : $\forall l \cdot l \in \{III, aVL, aVF, V1, V2\} \Rightarrow T_Wave_State_B(l) = Variable$

then

act1 : T_Normal_Status := TRUE

end

Event *T_Wave_Assessment_B_DI* ≐

abnormal T wavein B ...DI(Definite Ischemia)

extends *T_Wave_Assessment_B_DI*

when

grd1 : $\forall l \cdot l \in LEADS \Rightarrow T_Wave_State(l) = Inverted$
grd2 : $\forall l \cdot l \in LEADS \Rightarrow ST_elevation(l) = TRUE$
 \vee
 $(Q_Normal_Status = FALSE)$
grd3 : T_Normal_Status = FALSE
 added in step-8 B

```

grd5 : Heart_State = KO
grd4 :  $\exists l, k. l \in LEADS \wedge k \in LEADS \wedge$ 
       $((ST\_seg\_ele(l) \geq 1000 \wedge ST\_seg\_ele(k) \geq 1000) \vee$ 
       $(ST\_elevation(l) = TRUE \wedge ST\_elevation(k) = TRUE))$ 
       $\vee$ 
       $(Abnormal\_Shaped\_ST(l) = TRUE \wedge Abnormal\_Shaped\_ST(k) = TRUE))$ 
       $\wedge$ 
       $l \neq k$ 
      added in step-8 B

then
  act1 : Disease_step8 := Definite_ischemia
end

Event T_Inversion_Likely_Ischemia  $\hat{=}$ 
  probable Ischemia or Likly ischemia

extends T_Inversion_Likely_Ischemia

when
  grd1 :  $\forall l. l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$ 
  grd2 :  $\forall l. l \in LEADS \Rightarrow ST\_elevation(l) = TRUE$ 
       $\vee$ 
       $Q\_Normal\_Status = FALSE$ 
  grd3 :  $\forall l. l \in LEADS \Rightarrow T\_inversion(l) > 5000$ 
      1 mm= 1000
  grd4 :  $\vee$ 
       $(\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
       $((ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE)$ 
       $\vee$ 
       $((ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000)$ 
       $\wedge$ 
       $(Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE)))$ 
       $\Rightarrow l1 \neq k1))$ 
grd5 :  $T\_inversion\_l.d(V2) = Localized \wedge$ 
       $T\_inversion\_l.d(V3) = Localized \wedge$ 
       $T\_inversion\_l.d(V4) = Localized \wedge$ 
       $T\_inversion\_l.d(V5) = Localized$ 
grd6 :  $T\_inversion\_l.d(II) = Localized \wedge$ 
       $T\_inversion\_l.d(III) = Localized \wedge$ 
       $T\_inversion\_l.d(aVF) = Localized$ 
      b. of Deep inversion  $i$  5mm
grd7 : Heart_State = KO
grd8 :  $T\_Normal\_Status = FALSE$ 

then
  act1 : Disease_step8 := Probable_ischemia
end

Event T_Inversion_Diffuse_B  $\hat{=}$ 
  Step 8 B for c.

extends T_Inversion_Diffuse_B

when

```

```

    grd1 :
      ∨
      (( $\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
      ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
      ∨
      ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
      ∧
      ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ )))
      ⇒  $l1 \neq k1$ )
grd2 :  $\forall l. l \in LEADS \Rightarrow T\_inversion(l) > 5000$ 
grd3 :  $\forall l. l \in LEADS \Rightarrow T\_inversion\_l.d(l) = Diffuse$ 
grd4 : Heart_State = K0
grd5 : T_Normal_Status = FALSE
  then
    act1 : Disease_step8.B ∈ {Cardiomyopathy, other_nonspecific}
  end
Event Axis_Assessment_QRS_upright_Yes_Age_less_40 ≐
extends Axis_Assessment_QRS_upright_Yes_Age_less_40
  any
    age
  where
    grd1 : QRS_Axis_State(I) = D.Upright ∧
           QRS_Axis_State(aVF) = D.Upright
    grd2 : age ∈ ℕ ∧ age < 40
  then
    act1 : minAngle := 0
    act2 : maxAngle := 110
  end
Event Axis_Assessment_QRS_upright_Yes_Age_gre_40 ≐
extends Axis_Assessment_QRS_upright_Yes_Age_gre_40
  any
    age
  where
    grd1 : QRS_Axis_State(I) = D.Upright ∧
           QRS_Axis_State(aVF) = D.Upright
    grd2 : age ∈ ℕ ∧ age > 40
  then
    act1 : minAngle := -30
    act2 : maxAngle := 90
  end
Event Axis_Assessment_QRS_upright_No_QRS_positive ≐
extends Axis_Assessment_QRS_upright_No_QRS_positive
  when
    grd1 : ¬(QRS_Axis_State(I) = D.Upright ∧
             QRS_Axis_State(aVF) = D.Upright)

```

```

    grd2 : QRS_Axis_State(I) = D_Positive ∧
           QRS_Axis_State(aVF) = D_Positive
    grd3 : Heart_State = KO
  then
    act1 : minAngle := -30
    act2 : maxAngle := -90
    act3 : Axis_Devi := LAD
  end
Event Axis_Assessment_QRS_upright_No_QRS_negative ≐
extends Axis_Assessment_QRS_upright_No_QRS_negative
  when
    grd1 : ¬(QRS_Axis_State(I) = D_Upright ∧
             QRS_Axis_State(aVF) = D_Upright)
    grd2 : QRS_Axis_State(I) = D_Negative ∧
           QRS_Axis_State(aVF) = D_Negative
    grd3 : Heart_State = KO
  then
    act1 : minAngle := 110
    act2 : maxAngle := 180
    act3 : Axis_Devi := RAD
  end
Event Misc_Disease_Step9_LAD ≐
extends Misc_Disease_Step9_LAD
  when
    grd1 : Axis_Devi = LAD ∧
           minAngle = -30 ∧
           maxAngle = -90
    grd2 : Heart_State = KO
  then
    act1 : Disease_step9 ∈ {LAFB, MSCHD, Some_Form_VT, ED_OC}
  end
Event Misc_Disease_Step9_RAD ≐
extends Misc_Disease_Step9_RAD
  when
    grd1 : Axis_Devi = RAD ∧
           minAngle = 110 ∧
           maxAngle = 180
    grd2 : Heart_State = KO
  then
    act1 : Disease_step9 ∈ {LPFB, NV_MSEC}
  end
Event R_Q_Assessment_R_Abnormal_V56_axis_deviation ≐
extends R_Q_Assessment_R_Abnormal_V56_axis_deviation

```

```

when
  grd1 : Q_Wave_State(V5) = TRUE ∧
        Q_Wave_State(V6) = TRUE
  grd2 : Axis_Devi = RAD ∧
        minAngle = 110 ∧
        maxAngle = 180
  grd3 : Heart_State = KO
then
  act1 : Disease_step5 := lateral_MI
end

Event Miscellaneous_Conditions_Step10 ≐
extends Miscellaneous_Conditions_Step10

when
  grd1 : MC_Step10_Test_Needed = TRUE
  grd2 : Heart_State = KO
then
  act1 : Disease_step10 := {Incomplete_RBBB, Pericarditis, Long_QT, Hypokalemia,
    Digitalis_toxicity, Electrical_alternans, Electronic_pacing, Hypothermia, Hypercalcemia}
end

Event Misc_Disease_Step10_Dextrcardia_Test ≐
extends Misc_Disease_Step10_Dextrcardia_Test

when
  grd1 : Axis_Devi = RAD ∧
        minAngle = 110 ∧
        maxAngle = 180
  grd2 : MC_Step10_Test_Needed = TRUE
  grd3 : Heart_State = KO
then
  act1 : Disease_step9 := Dextrocardia
end

Event Rhythm_test_FALSE_Step11 ≐
extends Rhythm_test_FALSE_Step11

any
  rate
where
  grd1 : (∀1..1 ∈ {II, V1, V2} ⇒ PP_Int.equidistant(1) = FALSE ∨
    RR_Int.equidistant(1) = FALSE ∨
    RR_Interval(1) ≠ PP_Interval(1))
    ∨
    P_Positive(II) = FALSE
  grd2 : rate ∈ 1..300
  grd5 : rate ∈ 1..300
then
  act1 : Sinus := No
  act2 : Heart_Rate := rate

```

```

act3 : Heart_State := KO
act4 : Disease_step11 ∈ {Atrial_Premature_Beats, Ventricular_Premature_Beats,
    Nodal_Premature_Beats, Bradyarrhythmias, Narrow_QRS_Tachycardias, Wide_QRS_Tachycardias}
end

Event Step11_N_QRS_Tachycardia ≐
    Narrow_QRS_achycardia_Regular...

when
    grd1 : Sinus = No
    grd2 : Heart_State = KO
    grd3 : Heart_Rate ∈ 1 .. 300 \ 60 .. 100
    grd4 : Disease_step11 = Narrow_QRS_Tachycardias
then
    act1 : Disease_step11_NW_QRST ∈ {Sinus_Tachycardia, AVNRT, AF_Fixed_AV_Conduction,
        AT_Paroxysmal_NParoxysmal, WPW_Syndromе_OCMT, Atrial_Fibrillation,
        AF_Variable_AV_Conduction, AT_Variable_AV_Block, Multifocal_Atrial_Tachycardia}
end

Event Step11_W_QRS_Tachycardia ≐
    Wide_QRS_achycardia_Regular...

when
    grd1 : Sinus = No
    grd2 : Heart_State = KO
    grd3 : Heart_Rate ∈ 1 .. 300 \ 60 .. 100
    grd4 : Disease_step11 = Wide_QRS_Tachycardias
then
    act1 : Disease_step11_NW_QRST ∈ {Ventricular_Tachycardia, Supraventricular_Tachycardia,
        AVNRT, WPW_Syndromе_Orthodromic, Sinus_Tachycardia, Atrial_Tachycardia,
        AF_Fixed_AV_Conduction, WPW_Syndromе_Antidromic, AF_BBB_WPW_Synd_Antidromic,
        AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti, Torsades_de_pointes}
end

END

```

An Event-B Specification of Step11_Abnormal_Rhythm_Ref2
Generated Date: 25 Nov 2010 @ 03:39:56 PM

MACHINE Step11_Abnormal_Rhythm_Ref2

REFINES Step11_Abnormal_Rhythm_Ref1

SEES Leads_ctx, Disease_Codes_ctx, Step5_ctx, Step6_ctx, Step8_ctx, Step9, Step10_ctx, Step11_ctx

VARIABLES

RR_Int_equidistant RR Interval
PP_Int_equidistant PP Interval
P_Positive P wave positive or negative
Sinus Sinus Rhythm
Heart_Rate Heart Rate in BPM
Heart_State OK or KO for heart state after ECG Interpretation
PR_Int PR Interval
Disease_step2 At level 2 Disease Codes
QRS_Int QRS Interval
M_Shape_Complex M-shaped complex in Leads
Slurred_S Slurred S wave in Leads
Notched_R Notched R wave in Leads
Small_R_QS A small R or QS wave in V1 and V2
Slurred_S_duration Slurred S duration
Delta_Wave Delta Wave
Disease_step3
ST_elevation ST segment elevation (Coved or Saddle-back)
Epsilon_Wave Epsilon Wave or (a terminal notch in the QRS)
ST_seg_ele ST segment for elevation 1mm=0.1mV
Disease_step4
Q_Width Q wave width
Q_Depth Q wave depth
Q_Normal_Status Q wave normal or abnormal
Age_of_Inf Age of Infarct
Disease_step5
Mice_State
R_Depth R wave depth or height (also use in Step 7)
R_Normal_Status R wave normal or abnormal
Q_Wave_State Q wave states for all LEADS
P_Wave_Peak function to estimate the peak of LEADS signal
Disease_step6
PP_Interval
RR_Interval
Diphasic
P_Wave_Broad

S_Depth S wave depth or height
R_S_Ratio R wave and S wave Ratio function
T_Wave_State T wave patterns...
Disease_step8
T_Wave_State_B B for alternative method of T wave assessment
T_Normal_Status T wave normal or abnormal
Abnormal_Shaped_ST
Asy_T_Inversion_strain Asymmetric T wave Inversion strain pattern
T_inversion Deep T wave inversion
T_inversion_l_d T inversion Localized and Diffuse
Disease_step8_B
QRS_Axis_State QRS Axis Direction
minAngle min. value of angle of Axis in degree
maxAngle max. value of angle of Axis in degree
Axis_Devi Axis Deviation in LEADS...
Disease_step9
Disease_step10
MC_Step10_Test_Needed Miscellaneous Conditions test in Step 10
Disease_step11
Disease_step11_NW_QRST
NW_QRS_Tachycardia_RT_State QRS Tachycardia Regular or Irregular State
ST_depression

INVARIANTS

inv1: $NW_QRS_Tachycardia_RT_State \in NW_QRS_Tachycardia_RI$
inv2: $NW_QRS_Tachycardia_RT_State = Regular \wedge Disease_step11_NW_QRST \in \{Sinus_Tachycardia, AVNRT, AF_Fixed_AV_Conduction, AT_Paroxysmal_NParoxysmal, WPW_Syndrome_OCMT\}$
 $\Rightarrow Heart_State = KO$
inv3: $NW_QRS_Tachycardia_RT_State = Irregular \wedge Disease_step11_NW_QRST \in \{Atrial_Fibrillation, AF_Variable_AV_Conduction, AT_Variable_AV_Block, Multifocal_Atrial_Tachycardia\}$
 $\Rightarrow Heart_State = KO$
inv4: $NW_QRS_Tachycardia_RT_State = Regular \wedge Disease_step11_NW_QRST \in \{Ventricular_Tachycardia, Supraventricular_Tachycardia, AVNRT, WPW_Syndrome_Orthodromic, Sinus_Tachycardia, Atrial_Tachycardia, AF_Fixed_AV_Conduction, WPW_Syndrome_Antidromic\}$
 $\Rightarrow Heart_State = KO$
inv5: $NW_QRS_Tachycardia_RT_State = Irregular \wedge Disease_step11_NW_QRST \in \{AF_BBB_WPW_Synd_Antidromic, AF_Variable_AV_Conduction_BBB_WPW_Synd_Anti, Torsades_de_pointes\}$
 $\Rightarrow Heart_State = KO$

EVENTS

Initialisation

extended

begin

act1: $RR_Int_equidistant \in LEADS \rightarrow BOOL$
act2: $PP_Int_equidistant \in LEADS \rightarrow BOOL$
act3: $P_Positive \in LEADS \rightarrow BOOL$

```

act4 : Sinus := No
act5 : PP.Interval :∈ LEADS → ℕ
act6 : RR.Interval :∈ LEADS → ℕ
act7 : Heart_Rate :∈ 1 .. 300
act8 : Heart_State := KO
act9 : PR.Int := 120
act10 : Disease_step2 := NDS2
act11 : QRS_Int := 50
act12 : Notched_R :∈ LEADS → BOOL
act13 : Small_R_QS :∈ LEADS → BOOL
act14 : Slurred_S_duration :∈ LEADS → ℕ1
act15 : M.Shape_Complex :∈ LEADS → BOOL
act16 : Slurred_S :∈ LEADS → BOOL
act17 : ST_elevation :∈ LEADS → BOOL
act18 : Epsilon_Wave :∈ LEADS → BOOL
act19 : Delta_Wave := 0
act20 : Disease_step3 := NDS3
act21 : ST_seg_ele :∈ LEADS → ℕ
act22 : Disease_step4 := NDS4
act57 : ST_depression :∈ LEADS → ℕ
act23 : Q_Width :∈ LEADS → ℕ
act24 : Q_Depth :∈ LEADS → ℕ
act25 : Q_Normal_Status := FALSE
act26 : Mice_State := NMS
act27 : R_Depth :∈ LEADS → ℕ
act28 : R_Normal_Status := FALSE
act29 : Q_Wave_State :∈ LEADS → BOOL
act30 : Age_of_Inf :∈ Age_of_Infarct
act31 : Disease_step5 := NDS5
act32 : Diphasic :∈ LEADS → BOOL
act33 : P_Wave_Broad :∈ LEADS → ℕ
act34 : P_Wave_Peak :∈ LEADS → ℕ
act35 : Disease_step6 := NDS6
act36 : S_Depth :∈ LEADS → ℕ
act37 : R_S_Ratio :∈ LEADS → ℕ
act38 : T_Wave_State :∈ LEADS → T_State
act39 : Disease_step8 := NDS8
act40 : Abnormal_Shaped_ST :∈ LEADS → BOOL
act41 : Asy_T_Inversion_strain :∈ LEADS → BOOL
act43 : T_inversion_l_d :∈ LEADS → T_State_l_d
act42 : T_inversion :∈ LEADS → ℕ
act44 : Disease_step8_B := NDS8B
act45 : T_Wave_State_B :∈ LEADS → T_State_B
act46 : T_Normal_Status := FALSE
act47 : QRS_Axis_State :∈ LEADS → QRS.directions
act48 : minAngle := 0
act49 : maxAngle := 0
act50 : Axis_Devi := ND
act51 : Disease_step9 := NDS9
act52 : Disease_step10 := NDS10

```

```

act53 : MC_Step10_Test_Needed := FALSE
act54 : Disease_step11 := NDS11
act55 : Disease_step11_NW_QRST := NDS11_NW_QRS
act56 : NW_QRS_Tachycardia_RT_State := NW_QRS_Tachycardia_RT
end

Event Rhythm_test_TRUE  $\hat{=}$ 
  Sinus Rhythm with Normal Rate
extends Rhythm_test_TRUE

any
  rate
where
  grd1 : ( $\exists l \cdot l \in \{II, V1, V2\} \wedge PP\_Int\_equidistant(l) = TRUE \wedge$ 
    RR_Int_equidistant(l) = TRUE  $\wedge$ 
    RR_Interval(l) = PP_Interval(l))
     $\wedge$ 
    P_Positive(II) = TRUE
  grd4 : rate  $\in$  60..100
    60..100 is the range of normal heart rate
  grd5 : PR_Int  $\leq$  200
    Heart is Normal if PR  $\leq$  200 QRS_Int < 120
    Heart is Normal if QRS < 120
  grd7 : Disease_step2 = NDS2
  grd8 : Disease_step3 = NDS3
  grd9 : Disease_step4 = NDS4
  grd10 : Disease_step5 = NDS5
  grd11 : Disease_step6 = NDS6
  grd12 : Disease_step8 = NDS8
  grd13 : Disease_step8_B = NDS8B
  grd14 : Disease_step9 = NDS9
  grd15 : Disease_step10 = NDS10
  grd16 : Disease_step11 = NDS11
  grd17 : Disease_step11_NW_QRST = NDS11_NW_QRS
then
  act1 : Sinus := Yes
  act2 : Heart_Rate := rate
  act3 : Heart_State := OK
end

Event Rhythm_test_FALSE  $\hat{=}$ 
  Abnormal Rhythm with Rate
extends Rhythm_test_FALSE

any
  rate
where
  grd1 : ( $\forall l \cdot l \in \{II, V1, V2\} \Rightarrow PP\_Int\_equidistant(l) = FALSE \vee$ 
    RR_Int_equidistant(l) = FALSE  $\vee$ 
    RR_Interval(l)  $\neq$  PP_Interval(l))
     $\vee$ 
    P_Positive(II) = FALSE

```

```

    grd2 : rate ∈ 1 .. 300
  then
    act1 : Sinus := No
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end
Event Rhythm_test.TRUE_Rate ≐
  Sinus Rhythm with abnormal Rate
extends Rhythm_test.TRUE_Rate
  any
    rate
  where
    grd1 : (∃l·l ∈ {II, V1, V2} ∧ PP.Int.equidistant(l) = TRUE ∧
      RR.Int.equidistant(l) = TRUE ∧
      RR.Interval(l) = PP.Interval(l))
      ∧
      P_Positive(II) = TRUE
    grd5 : rate ∈ 1 .. 300 \ 60 .. 100
      60..100 is the range of normal heart rate, so rest of no. is abnormal
    grd6 : Disease_step3 = WPW.Syndrome ∨ Disease_step3 = Brugada.Syndrome ∨
      Disease_step3 = RV_Dysplasia ∨ Disease_step3 = IVCD
  then
    act1 : Sinus := Yes
    act2 : Heart_Rate := rate
    act3 : Heart_State := KO
  end
Event PR_Test ≐
  PR Interval Test
extends PR_Test
  any
    pr
  where
    grd1 : pr ∈ 120 .. 220
      time interval in (ms.)
    grd2 : pr > 200
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
  then
    act1 : PR.Int := pr
    act2 : Disease_step2 := First_degree_AV_Block
  end
Event QRS_Test_LBBB ≐
  QRS Complex Interval Test
extends QRS_Test_LBBB
  any

```

```

    qrs
  where
    grd1 : qrs ∈ 50 .. 150
    grd2 : qrs ≥ 120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : Notched_R(I) = TRUE ∧
           Notched_R(V5) = TRUE ∧
           Notched_R(V6) = TRUE
           Right Bundle Branch Block (RBBB)
    grd6 : Small_R_QS(V1) = TRUE ∧
           Small_R_QS(V2) = TRUE
    grd7 : Q_Wave_State(V1) = TRUE ∧
           Q_Wave_State(V2) = TRUE ∧
           Q_Wave_State(V3) = TRUE ∧
           Q_Wave_State(V4) = TRUE
           from step 5
    grd8 : R_Normal_Status = FALSE
           from step 5
    grd9 : Axis_Devi = LAD ∧
           minAngle = -30 ∧
           maxAngle = -90
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := LBBB
  end
Event QRS_Test_RBBB ≐
  Right Bundle Branch Block (RBBB)
extends QRS_Test_RBBB
  any
    qrs
  where
    grd1 : qrs ∈ 50 .. 150
    grd2 : qrs ≥ 120
    grd3 : Sinus = Yes
    grd4 : Heart_State = KO
    grd5 : M_Shape_Complex(V1) = TRUE ∧
           M_Shape_Complex(V2) = TRUE
    grd7 : Slurred_S(I) = TRUE ∧
           Slurred_S(V5) = TRUE ∧
           Slurred_S(V6) = TRUE
    grd8 : Slurred_S_duration(I) > 40 ∧
           Slurred_S_duration(V5) > 40 ∧
           Slurred_S_duration(V6) > 40
  then
    act1 : QRS_Int := qrs
    act2 : Disease_step2 := RBBB
  end
end

```

Event *QRS_Test_Atypical_RLBBB_WPW_Syndrome* $\hat{=}$
QRS Test for Atypical LBBB RBBB

extends *QRS_Test_Atypical_RLBBB_WPW_Syndrome*

any

sympt
d_wave
exmi

where

grd1 : QRS_Int \geq 110
grd2 : sympt = A_RBBB \vee sympt = A_LBBB
grd3 : d_wave \in \mathbb{N}
grd4 : (d_wave + PR_Int) \leq 120
Delta Wave + PR \leq 120 Heart_State = KO
grd5 : Disease_step4 = Acute_inferior_MI
grd6 : Disease_step4 = Acute_inferior_MI
grd7 : exmi \in Mice_State5 \wedge exmi = Exclude_Mimics_MI

then

act2 : Delta_Wave := d_wave
act3 : Disease_step3 := WPW_Syndrome

end

Event *QRS_Test_Atypical_RBBB_Brugada_Syndrome* $\hat{=}$

Atypical RBBB but WPW Excluded and no slurred S wave in V5 and V6

extends *QRS_Test_Atypical_RBBB_Brugada_Syndrome*

any

sympt
dis

where

grd1 : sympt = A_RBBB
grd2 : Heart_State = KO
grd3 : QRS_Int \geq 110
grd4 : Slurred_S(V5) = FALSE \wedge
Slurred_S(V6) = FALSE
grd5 : dis \in Disease_Codes_Step3 \setminus {WPW_Syndrome, NDS3}
grd6 : ST_elevation(V1) = TRUE \wedge
ST_elevation(V2) = TRUE
grd7 : Sinus = Yes

then

act1 : Disease_step3 := Brugada_Syndrome

end

Event *QRS_Test_Atypical_RBBB_RV_Dysplasia* $\hat{=}$

Right Ventricular Dysplasia

extends *QRS_Test_Atypical_RBBB_RV_Dysplasia*

any

sympt
dis

where

```

    grd1 : sympt = A_RBBB
    grd2 : Heart.State = KO
    grd3 : QRS_Int ≥ 110
    grd4 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, NDS3}
    grd5 : Epsilon_Wave(V1) = TRUE ∧
           Epsilon_Wave(V3) = TRUE
  then
    act1 : Disease_step3 := RV_Dysplasia
  end
Event QRS_Test_Atypical_RBBB_IVCD ≐
  IVCD diagnosis
extends QRS_Test_Atypical_RBBB_IVCD
  any
    dis
  where
    grd1 : QRS_Int ≥ 110
    grd2 : dis ∈ Disease_Codes_Step3 \ {WPW_Syndrome, Brugada_Syndrome, RV_Dysplasia, NDS3}
    grd3 : Heart.State = KO
  then
    act1 : Disease_step3 := IVCD
  end
Event ST_seg_elevation_YES ≐
  ST segment elevation...
extends ST_seg_elevation_YES
  when
    grd1 : Heart.State = KO
    grd2 : Sinus = Yes
    grd3 :
      ∨
      ((∃ l1, k1 · l1 ∈ {V1, V2, V3, V4, V5, V6} ∧ k1 ∈ {V1, V2, V3, V4, V5, V6} ∧
      (ST_elevation(l1) = TRUE ∧ ST_elevation(k1) = TRUE)
      ∧
      (ST_seg_ele(l1) ≥ 1000 ∧ ST_seg_ele(k1) ≥ 1000)
      ∧ l1 ≠ k1
      ∧
      (
      (l1 = V1 ∧ k1 = V2) ∨
      (l1 = V2 ∧ k1 = V3) ∨
      (l1 = V3 ∧ k1 = V4) ∨
      (l1 = V4 ∧ k1 = V5) ∨
      (l1 = V5 ∧ k1 = V6)
      )
      ))
    grd4 : Disease_step4 ∈ {Acute_inferior_MI, Acute_anterior_MI}
  then
    act1 : Disease_step4 := STEMI
  end
Event ST_seg_elevation_NOTCKMB_Yes ≐
  Troponin or CK-MB positive YES

```

```

extends ST_seg_elevation_NOTCKMB_Yes
  when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :
       $\vee$ 
       $(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$ 
         $(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$ 
grd4 :  $\exists l, k \cdot l \in LEADS \wedge k \in LEADS \wedge$ 
       $(ST\_depression(l) \geq 1000 \wedge ST\_depression(k) \geq 1000$ 
         $\wedge l \neq k$ 
grd5 : Disease_step4  $\in$  {Troponin, CK_MB}
  then
    act1 : Disease_step4 := Non_STEMI
  end

Event ST_seg_elevation_NO_TCKMB_No  $\hat{=}$ 
  Troponin or CK-MB positive No

extends ST_seg_elevation_NO_TCKMB_No
  when
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :
       $\vee$ 
       $(\forall l1 \cdot l1 \in \{II, III, aVF\} \Rightarrow$ 
         $(ST\_elevation(l1) = FALSE \wedge ST\_seg\_ele(l1) < 1000))$ 
grd4 :  $\exists l, k \cdot l \in LEADS \wedge k \in LEADS \wedge$ 
       $(ST\_depression(l) \geq 1000 \wedge ST\_depression(k) \geq 1000$ 
         $\wedge l \neq k$ 
grd5 : Disease_step4  $\notin$  {Troponin, CK_MB}
grd6 :  $\forall l \cdot l \in LEADS \Rightarrow T\_inversion(l) < 5000$ 
grd7 : T_Normal_Status = FALSE
  then
    act1 : Disease_step4 := Ischemia
  end

Event Q_Assessment_Normal  $\hat{=}$ 
  Q wave assessment normal

extends Q_Assessment_Normal
  when
    grd1 :  $Q\_Width(II) < 40 \wedge Q\_Depth(II) \leq 3000 \wedge$ 
       $Q\_Width(aVF) < 40 \wedge Q\_Depth(aVF) \leq 3000 \wedge$ 
       $Q\_Width(aVL) < 40$ 
      1000 micrometer= 1 millimeter
    grd2 :  $Q\_Width(III) \leq 40 \wedge Q\_Depth(III) \leq 7000 \wedge Q\_Depth(aVL) \leq 7000$ 
    grd3 :  $Q\_Depth(I) < 40 \wedge Q\_Depth(I) \leq 1500$ 
  then
    act1 : Q_Normal_Status := TRUE
  end

Event Q_Assessment_Abnormal_AMI  $\hat{=}$ 
  Q wave assessment abnormal for anterolateral MI (AMI)

```


extends *Q_Assessment_Abnormal_AMI*

when

```
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :  $\vee$ 
      (( $\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
      ( $ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE$ )
       $\wedge$ 
      ( $ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000$ )
       $\wedge l1 \neq k1$ 
       $\wedge$ 
      (
      ( $l1 = V1 \wedge k1 = V2$ )  $\vee$ 
      ( $l1 = V2 \wedge k1 = V3$ )  $\vee$ 
      ( $l1 = V3 \wedge k1 = V4$ )  $\vee$ 
      ( $l1 = V4 \wedge k1 = V5$ )  $\vee$ 
      ( $l1 = V5 \wedge k1 = V6$ )
      )
      ))
```

```
grd4 : Q_Width(V5)  $\geq$  40  $\wedge$  Q_Depth(V5)  $>$  3000  $\wedge$ 
      Q_Width(V6)  $\geq$  40  $\wedge$  Q_Depth(V6)  $>$  3000
```

```
grd5 : Q_Width(aVL)  $\geq$  40  $\wedge$  Q_Depth(aVL)  $>$  7000
```

```
grd6 : Q_Depth(I)  $\geq$  40  $\wedge$  Q_Depth(I)  $>$  1500
```

```
grd7 : Q_Normal_Status = FALSE
```

then

```
    act1 : Disease_step4 := Acute_anterior_MI
```

end

Event *Q_Assessment_Abnormal_IMI* $\hat{=}$

Q wave assessment abnormal for inferior MI (IMI)

extends *Q_Assessment_Abnormal_IMI*

when

```
    grd1 : Heart_State = KO
    grd2 : Sinus = Yes
    grd3 :  $\vee$ 
      (( $\exists l1, k1 \cdot l1 \in \{V1, V2, V3, V4, V5, V6\} \wedge k1 \in \{V1, V2, V3, V4, V5, V6\} \wedge$ 
      ( $ST\_elevation(l1) = TRUE \wedge ST\_elevation(k1) = TRUE$ )
       $\wedge$ 
      ( $ST\_seg\_ele(l1) \geq 1000 \wedge ST\_seg\_ele(k1) \geq 1000$ )
       $\wedge l1 \neq k1$ 
       $\wedge$ 
      (
      ( $l1 = V1 \wedge k1 = V2$ )  $\vee$ 
      ( $l1 = V2 \wedge k1 = V3$ )  $\vee$ 
      ( $l1 = V3 \wedge k1 = V4$ )  $\vee$ 
      ( $l1 = V4 \wedge k1 = V5$ )  $\vee$ 
      ( $l1 = V5 \wedge k1 = V6$ )
      )
      ))
```

```
grd4 : Q_Width(II)  $\geq$  40  $\wedge$  Q_Depth(II)  $>$  3000  $\wedge$ 
      Q_Width(III)  $>$  40  $\wedge$  Q_Depth(III)  $>$  7000  $\wedge$ 
      Q_Width(aVF)  $\geq$  40  $\wedge$  Q_Depth(aVF)  $>$  3000
```

```
grd5 : Q_Normal_Status = FALSE
```

```

    then
        act1 : Disease_step4 := Acute_inferior_MI
    end
Event Determine_Age_of_Infarct  $\hat{=}$ 
extends Determine_Age_of_Infarct
    when
        grd1 : Disease_step4 = Acute_inferior_MI
             $\vee$ 
            Disease_step5  $\in$  {anterior_MI, LVH, emphysema}
             $\vee$ 
            Mice_State = Exclude_Mimics_MI
             $\vee$ 
            Disease_step2 = LBBB
    then
        act1 : Age_of_Inf  $\in$  {recent, old, indeterminate}
    end
Event Exclude_Mimics  $\hat{=}$ 
extends Exclude_Mimics
    any
        exmi
    where
        grd1 : Disease_step4 = Acute_inferior_MI
        grd2 : exmi  $\in$  Mice_State5  $\wedge$  exmi = Exclude_Mimics_MI
    then
        act1 : Disease_step5 := Hypertrophic_cardiomyopathy
        act2 : Mice_State := borderline_Qs
    end
Event R_Assessment_Normal  $\hat{=}$ 
    Q wave assessment normal
extends R_Assessment_Normal
    any
        age
    where
        grd1 : R.Depth(V1)  $\geq$  0  $\wedge$  R.Depth(V1)  $\leq$  6000  $\wedge$  age > 30
            1000 micrometer= 1 millimeter
        grd2 : R.Depth(V2) > 200  $\wedge$  R.Depth(V2)  $\leq$  12000
        grd3 : R.Depth(V2)  $\geq$  1000  $\wedge$  R.Depth(V2)  $\leq$  24000
    then
        act1 : R.Normal_Status := TRUE
    end
Event R_Assessment_Abnormal  $\hat{=}$ 
extends R_Assessment_Abnormal
    when

```

```

    grd1 : R.Normal_Status = FALSE
  then
    act1 : Mice_State ∈ {late_transition, normal_variant}
  end

Event R_Q_Assessment_R_Abnormal_V1234 ≐
  R wave abnormal , pathologic Q waves consider in V1-V4

extends R_Q_Assessment_R_Abnormal_V1234

  when
    grd1 : R.Normal_Status = FALSE
    grd2 : Q_Wave_State(V1) = TRUE ∧
           Q_Wave_State(V2) = TRUE ∧
           Q_Wave_State(V3) = TRUE ∧
           Q_Wave_State(V4) = TRUE
    grd3 : Heart_State = KO
  then
    act1 : Disease_step5 ∈ {anterior_MI, LVH, emphysema}
    act2 : Mice_State := Exclude_Mimics_MI
  end

Event R_Q_Assessment_R_Abnormal_V56 ≐
  R wave abnormal , pathologic Q waves consider in V5-V6

extends R_Q_Assessment_R_Abnormal_V56

  when
    grd1 : Q_Wave_State(V5) = TRUE ∧
           Q_Wave_State(V6) = TRUE
    grd2 : Heart_State = KO
  then
    act1 : Disease_step5 := Hypertrophic_cardiomyopathy
  end

Event P_Wave_assessment_Peaked_Broad_No ≐

extends P_Wave_assessment_Peaked_Broad_No

  when
    grd1 : (P_Wave_Peak(II) < 3000 ∧
           P_Wave_Peak(V1) < 3000)
           ∨
           (P_Wave_Broad(II) < 110 ∧ P_Wave_Broad(V1) < 110) ∨
           Diphasic(II) = FALSE ∨
           Diphasic(V1) = FALSE
  then
    act1 : Disease_step6 := NDS6
  end

Event P_Wave_assessment_Peaked_Yes ≐

extends P_Wave_assessment_Peaked_Yes

  when
    grd1 : P_Wave_Peak(II) ≥ 3000

```

```

    grd2 : P.Wave.Peak(V1) ≥ 3000
    grd3 : Heart.State = KO
  then
    act1 : Disease.step6 := RAE
  end
Event P.Wave.assessment.Peaked.Yes.Check.RAE ≐
extends P.Wave.assessment.Peaked.Yes.Check.RAE
  when
    grd1 : P.Wave.Peak(II) ≥ 3000
    grd2 : P.Wave.Peak(V1) ≥ 3000
    grd3 : Disease.step6 = RAE
    grd4 : Heart.State = KO
  then
    act1 : Disease.step6 := RV.strain
  end
Event P.Wave.assessment.Broad.Yes ≐
extends P.Wave.assessment.Broad.Yes
  when
    grd1 : (P.Wave.Broad(II) ≥ 110 ∧ P.Wave.Broad(V1) ≥ 110) ∨
      Diphasic(II) = TRUE ∨
      Diphasic(V1) = TRUE
    grd2 : Heart.State = KO
  then
    act1 : Disease.step6 := LAE
  end
Event P.Wave.assessment.Broad.Yes.Check.LAE ≐
extends P.Wave.assessment.Broad.Yes.Check.LAE
  when
    grd1 : (P.Wave.Broad(II) ≥ 110 ∧ P.Wave.Broad(V1) ≥ 110) ∨
      Diphasic(II) = TRUE ∨
      Diphasic(V1) = TRUE
    grd2 : Disease.step6 = LAE
    grd3 : Heart.State = KO
  then
    act1 : Disease.step6 ∈ {mitral_stenosis, mitral_regurgitation, LV_failure,
      dilated_cardiomyopathy}
  end
Event LVH.Assessment ≐
  LVH Assessment
extends LVH.Assessment
  any
    LVH_specificity    specificity in percentage
    sensitivity        sensitivity in percentage

```

```

sex
where
  grd1 : (P_Wave_Broad(II) ≥ 110 ∧ P_Wave_Broad(V1) ≥ 110) ∨
          Diphasic(II) = TRUE ∨
          Diphasic(V1) = TRUE
  grd2 : Disease_step6 = LAE
  grd5 : sex ∈ {0, 1}
          o for men and 1 for women
  grd3 : ((S_Depth(V1) + R_Depth(V5)) > 35000
          ∨
          (S_Depth(V1) + R_Depth(V6)) > 35000)
          1mm = 1000 micrometer..... 1 assessment
  grd4 : ((R_Depth(aVL) + S_Depth(V1) ≥ 24000) ∧ sex = 0)
          ∨
          ((R_Depth(aVL) + S_Depth(V1) ≥ 18000) ∧ sex = 1)
          2 assessment
  grd6 : LVH_specificity = 90
          ∧
          sensitivity < 40
          1 and 2 assessment
  grd7 : Disease_step6 = LAE ⇒ LVH_specificity < 98
          3 assessment
  grd8 : (∀t. t ∈ LEADS ⇒ ST_elevation(t) = TRUE
          ∨
          Q_Normal_Status = FALSE))
          A or B : from step 8 development
  grd9 : (∀l1, k1. l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
          ((ST_elevation(l1) = FALSE ∨ ST_elevation(k1) = FALSE)
          ∨
          ((ST_seg_ele(l1) < 1000 ∨ ST_seg_ele(k1) < 1000)
          ∧
          (Abnormal_Shaped_ST(l1) = FALSE ∨ Abnormal_Shaped_ST(k1) = FALSE)))
          ⇒ l1 ≠ k1))
  grd10 : Asy_T_Inversion_strain(V5) = TRUE ∧
           Asy_T_Inversion_strain(V6) = TRUE ∧
           Asy_T_Inversion_strain(V4) = TRUE
  grd11 : Heart_State = KO
  grd12 : T_Normal_Status = FALSE
  grd13 : Axis_Devi = LAD ∧
           minAngle = -30 ∧
           maxAngle = -90
then
  act1 : Disease_step6 := LVH_cause
end

Event RVH_Assessment ≐
RVH_Assessment

extends RVH_Assessment

any
  age    age of men or women
  axis   axis for deviation

```

where

```
grd1 : P.Wave.Peak(II) ≥ 3000
grd2 : P.Wave.Peak(V1) ≥ 3000
grd3 : Disease_step6 = RAE
grd4 : R.Depth(V1) ≥ 7000 ∧ age > 30
      1 assessment
grd5 : S.Depth(V5) ≥ 7000 ∨
      S.Depth(V6) ≥ 7000
      2 assessment
grd6 : R.S.Ratio(V1) ≥ 100
      R_S Ratio is multiply by 100 to remove the real no. constants... 3 assessment
grd7 : R.S.Ratio(V5) ≤ 100
      ∨
      R.S.Ratio(V6) ≤ 100
      4 assessment
grd8 : aixs ∈ 0..360 ∧ aixs ≥ 110
      5 assessment
grd9 : Disease_step2 ∉ {LBBB, RBBB}
grd10 : QRS_Int < 120
grd11 : (∀t·t ∈ LEADS ⇒ ST_elevation(t) = TRUE
      ∨
      Q_Normal_Status = FALSE))
```

AorB : from step8development

```
∨
(∀l1, k1·l1 ∈ LEADS ∧ k1 ∈ LEADS ∧
((ST_elevation(l1) = FALSE ∨ ST_elevation(k1) = FALSE)
∨
((ST_seg_ele(l1) < 1000 ∨ ST_seg_ele(k1) < 1000)
∧
(Abnormal_Shaped_ST(l1) = FALSE ∨ Abnormal_Shaped_ST(k1) = FALSE)))
⇒ l1 ≠ k1))
```

```
grd13 : Asy_T_Inversion_strain(V1) = TRUE ∧
Asy_T_Inversion_strain(V2) = TRUE ∧
Asy_T_Inversion_strain(V3) = TRUE
```

```
grd14 : Heart.State = KO
```

```
grd15 : T_Normal_Status = FALSE
```

```
grd16 : Axis_Devi = RAD ∧
minAngle = 110 ∧
maxAngle = 180
```

then

```
act1 : Disease_step6 := RVH
```

end

Event *T.Wave.Assessment.Peaked.V123456* $\hat{=}$

T Wave Assessment

extends *T.Wave.Assessment.Peaked.V123456*

when

```
grd1 : ∀l·l ∈ {V1, V2, V3, V4, V5, V6} ⇒ T.Wave.State(l) = Peaked
```

```
grd2 : MC_Step10_Test_Needed = TRUE
```

```
grd3 : Heart.State = KO
```

then

```

        act1 : Disease_step8 := Hyperkalemia
    end

Event T.Wave_Assessment_Peaked_V12  $\hat{=}$ 
extends T.Wave_Assessment_Peaked_V12

    when
        grd1 : R.Normal_Status = FALSE
        grd2 : T.Wave_State(V1) = Peaked  $\wedge$ 
              T.Wave_State(V2) = Peaked
        grd3 :  $\vee$ 
              (( $\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
                ((ST_elevation(l1) = FALSE  $\vee$  ST_elevation(k1) = FALSE)
                 $\vee$ 
                ((ST_seg_ele(l1) < 1000  $\vee$  ST_seg_ele(k1) < 1000)
                 $\wedge$ 
                (Abnormal_Shaped_ST(l1) = FALSE  $\vee$  Abnormal_Shaped_ST(k1) = FALSE)))
                 $\Rightarrow l1 \neq k1$ ))
        grd4 :  $\forall l. l \in LEADS \Rightarrow T.inversion(l) < 5000$ 
              step 8 B
        grd5 : T.Normal_Status = FALSE
        grd6 :  $\vee$ 
              (Axis_Devi = RAD  $\wedge$ 
               minAngle = 110  $\wedge$ 
               maxAngle = 180)
    then
        act1 : Mice_State := normal_variant
    end

Event T.Wave_Assessment_Peaked_V12_MI  $\hat{=}$ 
    posterior MI using T wave assessment in LEADS V1 and V2
extends T.Wave_Assessment_Peaked_V12_MI

    when
        grd1 : T.Wave_State(V1) = Peaked  $\wedge$ 
              T.Wave_State(V2) = Peaked
        grd6 : Heart_State = K0
        grd2 :  $\vee$ 
              (( $\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
                ((ST_elevation(l1) = FALSE  $\vee$  ST_elevation(k1) = FALSE)
                 $\vee$ 
                ((ST_seg_ele(l1) < 1000  $\vee$  ST_seg_ele(k1) < 1000)
                 $\wedge$ 
                (Abnormal_Shaped_ST(l1) = FALSE  $\vee$  Abnormal_Shaped_ST(k1) = FALSE)))
                 $\Rightarrow l1 \neq k1$ ))
        grd3 :  $\forall l. l \in LEADS \Rightarrow T.inversion(l) > 5000$ 
        grd4 : T.inversion_l.d(V2) = Localized  $\wedge$ 
              T.inversion_l.d(V3) = Localized  $\wedge$ 
              T.inversion_l.d(V4) = Localized  $\wedge$ 
              T.inversion_l.d(V5) = Localized
        grd5 : T.inversion_l.d(II) = Localized  $\wedge$ 
              T.inversion_l.d(III) = Localized  $\wedge$ 
              T.inversion_l.d(aVF) = Localized
        grd7 : T.Normal_Status = FALSE

```

```

    then
      act1 : Disease_step8 := posterior_MI
    end

Event T_Wave_Assessment_Flat  $\hat{=}$ 
extends T_Wave_Assessment_Flat

when
  grd1 :  $\forall l. l \in LEADS \Rightarrow T\_Wave\_State(l) = Flat$ 
  grd4 : Heart_State = KO
  grd2 :  $\bigvee$ 
    ( $\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
    ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
     $\vee$ 
    ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
     $\wedge$ 
    ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ ))
     $\Rightarrow l1 \neq k1$ )
step 8 B
grd3 :  $\forall l. l \in LEADS \Rightarrow T\_inversion(l) < 5000$ 
grd5 : T_Normal_Status = FALSE
  then
    act1 : Disease_step8 := Nonspecific_ST_T_changes
    act2 : Disease_step8_B  $\in$  {Cardiomyopathy, Electrolyte_depletion, Alcohol, Myocarditis, Other}
  end

Event T_Wave_Assessment_Inverted_Yes  $\hat{=}$ 
extends T_Wave_Assessment_Inverted_Yes

when
  grd1 :  $\forall l. l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$ 
  grd2 :  $\forall l. l \in LEADS \Rightarrow ST\_elevation(l) = TRUE$ 
     $\vee$ 
    Q_Normal_Status = FALSE
  grd3 : Heart_State = KO
  then
    act1 : Disease_step8  $\in$  {Definite_ischemia, Probable_ischemia, Digitalis_effect}
  end

Event T_Wave_Assessment_Inverted_No  $\hat{=}$ 
extends T_Wave_Assessment_Inverted_No

when
  grd1 :  $\forall l. l \in LEADS \Rightarrow T\_Wave\_State(l) = Inverted$ 
  grd2 :  $\forall l. l \in LEADS \Rightarrow ST\_elevation(l) = FALSE$ 
     $\vee$ 
    Q_Normal_Status = TRUE
  grd3 : Heart_State = KO
  then
    act1 : Disease_step8 := Nonspecific
  end
end

```


Event *T_Wave_Assessment_Inverted_Yes_PM* $\hat{=}$
 PM - pulmonary embolism this disease is already defined in previous development.

refines *T_Wave_Assessment_Inverted_Yes_PM*

when

grd1 : $P_Wave_Peak(II) \geq 3000$
grd2 : $P_Wave_Peak(V1) \geq 3000$
grd3 : $Disease_step6 = RAE$
grd4 : $(\forall t.t \in LEADS \Rightarrow ST_elevation(t) = TRUE$
 \vee
 $Q_Normal_Status = FALSE))$

A : *step8*

$\neg(\exists l, k.l \in LEADS \wedge k \in LEADS \wedge$
 $((ST_seg_ele(l) \geq 1000 \wedge ST_seg_ele(k) \geq 1000) \vee$
 $(ST_elevation(l) = TRUE \wedge ST_elevation(k) = TRUE)$
 \vee
 $(Abnormal_Shaped_ST(l) = TRUE \wedge Abnormal_Shaped_ST(k) = TRUE))$
 \Rightarrow
 $l \neq k))$

grd5 : $Asy_T_Inversion_strain(V1) = TRUE \wedge$
 $Asy_T_Inversion_strain(V2) = TRUE \wedge$
 $Asy_T_Inversion_strain(V3) = TRUE$

grd7 : $Axis_Devi = RAD \wedge$
 $minAngle = 110 \wedge$
 $maxAngle = 180$

grd8 : $MC_Step10_Test_Needed = TRUE$

grd9 : $Heart_State = KO$

then

act1 : $Disease_step6 := pulmonary_embolism$

end

Event *T_Wave_Assessment_B* $\hat{=}$

B for alternate method of T wave assessment

extends *T_Wave_Assessment_B*

when

grd1 : $\forall l.l \in \{I, II, V3, V4, V5, V6\} \Rightarrow T_Wave_State_B(l) = Upright$
grd2 : $T_Wave_State_B(aVL) = Inverted_B$
grd3 : $\forall l.l \in \{III, aVL, aVF, V1, V2\} \Rightarrow T_Wave_State_B(l) = Variable$

then

act1 : $T_Normal_Status := TRUE$

end

Event *T_Wave_Assessment_B_DI* $\hat{=}$

abnormal T wavein B ...DI(Definite Ischemia)

extends *T_Wave_Assessment_B_DI*

when

grd1 : $\forall l.l \in LEADS \Rightarrow T_Wave_State(l) = Inverted$
grd2 : $\forall l.l \in LEADS \Rightarrow ST_elevation(l) = TRUE$
 \vee
 $Q_Normal_Status = FALSE$

```

    grd3 : T_Normal_Status = FALSE
           added in step-8 B
    grd5 : Heart_State = KO
    grd4 :  $\exists l, k. l \in \text{LEADS} \wedge k \in \text{LEADS} \wedge$ 
            $((\text{ST\_seg\_ele}(l) \geq 1000 \wedge \text{ST\_seg\_ele}(k) \geq 1000) \vee$ 
            $(\text{ST\_elevation}(l) = \text{TRUE} \wedge \text{ST\_elevation}(k) = \text{TRUE}))$ 
            $\vee$ 
            $(\text{Abnormal\_Shaped\_ST}(l) = \text{TRUE} \wedge \text{Abnormal\_Shaped\_ST}(k) = \text{TRUE}))$ 
            $\wedge$ 
            $l \neq k$ 
           added in step-8 B

  then
    act1 : Disease_step8 := Definite_ischemia
  end

Event T_Inversion_Likely_Ischemia  $\hat{=}$ 
  probable Ischemia or Likly ischemia

extends T_Inversion_Likely_Ischemia

  when

    grd1 :  $\forall l. l \in \text{LEADS} \Rightarrow \text{T\_Wave\_State}(l) = \text{Inverted}$ 
    grd2 :  $\forall l. l \in \text{LEADS} \Rightarrow \text{ST\_elevation}(l) = \text{TRUE}$ 
            $\vee$ 
            $\text{Q\_Normal\_Status} = \text{FALSE}$ 
    grd3 :  $\forall l. l \in \text{LEADS} \Rightarrow \text{T\_inversion}(l) > 5000$ 
           1 mm= 1000
    grd4 :  $\vee$ 
            $(\forall l1, k1. l1 \in \text{LEADS} \wedge k1 \in \text{LEADS} \wedge$ 
            $((\text{ST\_elevation}(l1) = \text{FALSE} \vee \text{ST\_elevation}(k1) = \text{FALSE}))$ 
            $\vee$ 
            $((\text{ST\_seg\_ele}(l1) < 1000 \vee \text{ST\_seg\_ele}(k1) < 1000)$ 
            $\wedge$ 
            $(\text{Abnormal\_Shaped\_ST}(l1) = \text{FALSE} \vee \text{Abnormal\_Shaped\_ST}(k1) = \text{FALSE})))$ 
            $\Rightarrow l1 \neq k1)$ 
    grd5 :  $\text{T\_inversion\_l.d}(V2) = \text{Localized} \wedge$ 
            $\text{T\_inversion\_l.d}(V3) = \text{Localized} \wedge$ 
            $\text{T\_inversion\_l.d}(V4) = \text{Localized} \wedge$ 
            $\text{T\_inversion\_l.d}(V5) = \text{Localized}$ 
    grd6 :  $\text{T\_inversion\_l.d}(\text{II}) = \text{Localized} \wedge$ 
            $\text{T\_inversion\_l.d}(\text{III}) = \text{Localized} \wedge$ 
            $\text{T\_inversion\_l.d}(\text{aVF}) = \text{Localized}$ 
           b. of Deep inversion  $\dot{c}$  5mm
    grd7 : Heart_State = KO
    grd8 : T_Normal_Status = FALSE

  then
    act1 : Disease_step8 := Probable_ischemia
  end

Event T_Inversion_Diffuse_B  $\hat{=}$ 
  Step 8 B for c.

extends T_Inversion_Diffuse_B

  when

```

```

    grd1 :  $\bigvee$ 
      ( $\forall l1, k1. l1 \in LEADS \wedge k1 \in LEADS \wedge$ 
      ( $ST\_elevation(l1) = FALSE \vee ST\_elevation(k1) = FALSE$ )
       $\vee$ 
      ( $ST\_seg\_ele(l1) < 1000 \vee ST\_seg\_ele(k1) < 1000$ )
       $\wedge$ 
      ( $Abnormal\_Shaped\_ST(l1) = FALSE \vee Abnormal\_Shaped\_ST(k1) = FALSE$ ))
       $\Rightarrow l1 \neq k1$ )
grd2 :  $\forall l. l \in LEADS \Rightarrow T\_inversion(l) > 5000$ 
grd3 :  $\forall l. l \in LEADS \Rightarrow T\_inversion\_l.d(l) = Diffuse$ 
grd4 : Heart_State = K0
grd5 : T_Normal_Status = FALSE
  then
    act1 : Disease_step8.B  $\in$  {Cardiomyopathy, other_nonspecific}
  end
Event Axis_Assessment_QRS_upright_Yes_Age_less_40  $\hat{=}$ 
extends Axis_Assessment_QRS_upright_Yes_Age_less_40
  any
    age
  where
    grd1 : QRS_Axis_State(I) = D.Upright  $\wedge$ 
           QRS_Axis_State(aVF) = D.Upright
    grd2 : age  $\in \mathbb{N} \wedge$  age < 40
  then
    act1 : minAngle := 0
    act2 : maxAngle := 110
  end
Event Axis_Assessment_QRS_upright_Yes_Age_gre_40  $\hat{=}$ 
extends Axis_Assessment_QRS_upright_Yes_Age_gre_40
  any
    age
  where
    grd1 : QRS_Axis_State(I) = D.Upright  $\wedge$ 
           QRS_Axis_State(aVF) = D.Upright
    grd2 : age  $\in \mathbb{N} \wedge$  age > 40
  then
    act1 : minAngle := -30
    act2 : maxAngle := 90
  end
Event Axis_Assessment_QRS_upright_No_QRS_positive  $\hat{=}$ 
extends Axis_Assessment_QRS_upright_No_QRS_positive
  when
    grd1 :  $\neg$ (QRS_Axis_State(I) = D.Upright  $\wedge$ 
              QRS_Axis_State(aVF) = D.Upright)

```

```

    grd2 : QRS_Axis_State(I) = D.Positive ∧
           QRS_Axis_State(aVF) = D.Positive
    grd3 : Heart_State = KO
  then
    act1 : minAngle := -30
    act2 : maxAngle := -90
    act3 : Axis_Devi := LAD
  end
Event Axis_Assessment_QRS_upright_No_QRS_negative ≐
extends Axis_Assessment_QRS_upright_No_QRS_negative
  when
    grd1 : ¬(QRS_Axis_State(I) = D.Upright ∧
             QRS_Axis_State(aVF) = D.Upright)
    grd2 : QRS_Axis_State(I) = D.Negative ∧
           QRS_Axis_State(aVF) = D.Negative
    grd3 : Heart_State = KO
  then
    act1 : minAngle := 110
    act2 : maxAngle := 180
    act3 : Axis_Devi := RAD
  end
Event Misc_Disease_Step9_LAD ≐
extends Misc_Disease_Step9_LAD
  when
    grd1 : Axis_Devi = LAD ∧
           minAngle = -30 ∧
           maxAngle = -90
    grd2 : Heart_State = KO
  then
    act1 : Disease_step9 ∈ {LAFB, MSCHD, Some_Form_VT, ED_OC}
  end
Event Misc_Disease_Step9_RAD ≐
extends Misc_Disease_Step9_RAD
  when
    grd1 : Axis_Devi = RAD ∧
           minAngle = 110 ∧
           maxAngle = 180
    grd2 : Heart_State = KO
  then
    act1 : Disease_step9 ∈ {LPFB, NV_MSEC}
  end
Event R_Q_Assessment_R_Abnormal_V56_axis_deviation ≐
extends R_Q_Assessment_R_Abnormal_V56_axis_deviation

```

```

when
  grd1 : Q_Wave_State(V5) = TRUE ∧
        Q_Wave_State(V6) = TRUE
  grd2 : Axis_Devi = RAD ∧
        minAngle = 110 ∧
        maxAngle = 180
  grd3 : Heart_State = KO
then
  act1 : Disease_step5 := lateral_MI
end

Event Miscellaneous_Conditions_Step10 ≐
extends Miscellaneous_Conditions_Step10

when
  grd1 : MC_Step10_Test_Needed = TRUE
  grd2 : Heart_State = KO
then
  act1 : Disease_step10 := {Incomplete_RBBB, Pericarditis, Long_QT, Hypokalemia,
    Digitalis_toxicity, Electrical_alternans, Electronic_pacing, Hypothermia, Hypercalcemia}
end

Event Misc_Disease_Step10_Dextrcardia_Test ≐
extends Misc_Disease_Step10_Dextrcardia_Test

when
  grd1 : Axis_Devi = RAD ∧
        minAngle = 110 ∧
        maxAngle = 180
  grd2 : MC_Step10_Test_Needed = TRUE
  grd3 : Heart_State = KO
then
  act1 : Disease_step9 := Dextrocardia
end

Event Rhythm_test_FALSE_Step11 ≐
extends Rhythm_test_FALSE_Step11

any
  rate
where
  grd1 : (∀l. l ∈ {II, V1, V2} ⇒ PP_Int.equidistant(l) = FALSE ∨
    RR_Int.equidistant(l) = FALSE ∨
    RR_Interval(l) ≠ PP_Interval(l))
    ∨
    P_Positive(II) = FALSE
  grd2 : rate ∈ 1..300
  grd5 : rate ∈ 1..300
then
  act1 : Sinus := No
  act2 : Heart_Rate := rate

```

```

    act3 : Heart_State := KO
    act4 : Disease_step11 ∈ {Atrial_Premature_Beats, Ventricular_Premature_Beats,
        Nodal_Premature_Beats, Bradyarrhythmias, Narrow_QRS_Tachycardias, Wide_QRS_Tachycardias}
end

Event Step11_N_QRS_Tachycardia_Regular ≐
    Narrow_QRS_achycardia_Regular...

refines Step11_N_QRS_Tachycardia

    when

        grd1 : Sinus = No
        grd2 : Heart_State = KO
        grd3 : Heart_Rate ∈ 1 .. 300 \ 60 .. 100
        grd4 : Disease_step11 = Narrow_QRS_Tachycardias
        grd5 : NW_QRS_Tachycardia_RT_State = Regular

    then

        act1 : Disease_step11_NW_QRST ∈ {Sinus_Tachycardia, AVNRT,
            AF_Fixed_AV_Conduction, AT_Paroxysmal_NParoxysmal, WPW_Syndrome_OCMT}

    end

Event Step11_N_QRS_Tachycardia_Irregular ≐
    Narrow_QRS_achycardia_Irregular...

refines Step11_N_QRS_Tachycardia

    when

        grd1 : Sinus = No
        grd2 : Heart_State = KO
        grd3 : Heart_Rate ∈ 1 .. 300 \ 60 .. 100
        grd4 : Disease_step11 = Narrow_QRS_Tachycardias
        grd5 : NW_QRS_Tachycardia_RT_State = Irregular

    then

        act1 : Disease_step11_NW_QRST ∈ {Atrial_Fibrillation, AF_Variable_AV_Conduction,
            AT_Variable_AV_Block, Multifocal_Atrial_Tachycardia}

    end

Event Step11_W_QRS_Tachycardia_Regular ≐
    Wide_QRS_achycardia_Regular...

refines Step11_W_QRS_Tachycardia

    when

        grd1 : Sinus = No
        grd2 : Heart_State = KO
        grd3 : Heart_Rate ∈ 1 .. 300 \ 60 .. 100
        grd4 : Disease_step11 = Wide_QRS_Tachycardias
        grd5 : NW_QRS_Tachycardia_RT_State = Regular

    then

        act1 : Disease_step11_NW_QRST ∈ {Ventricular_Tachycardia, Supraventricular_Tachycardia,
            AVNRT, WPW_Syndrome_Orthodromic, Sinus_Tachycardia, Atrial_Tachycardia,
            AF_Fixed_AV_Conduction, WPW_Syndrome_Antidromic}

    end
end

```

```

Event Step11-W-QRS-Tachycardia-Irregular  $\hat{=}$ 
    Wide QRS achycardia Irregular....
refines Step11-W-QRS-Tachycardia
    when
        grd1 : Sinus = No
        grd2 : Heart_State = KO
        grd3 : Heart_Rate  $\in$  1 .. 300 \ 60 .. 100
        grd4 : Disease_step11 = Wide-QRS-Tachycardias
        grd5 : NW-QRS-Tachycardia-RT-State = Irregular
    then
        act1 : Disease_step11_NW-QRST  $\in$  {AF-BBB-WPW-Synd-Antidromic,
            AF-Variable-AV-Conduction-BBB-WPW-Synd-Anti, Torsades-de-pointes}
    end
END

```