



HAL
open science

Mathematical analysis of cardiac electromechanics with physiological ionic model

Mostafa Bendahmane, Fatima Mroue, Mazen Saad, Raafat Talhouk

► **To cite this version:**

Mostafa Bendahmane, Fatima Mroue, Mazen Saad, Raafat Talhouk. Mathematical analysis of cardiac electromechanics with physiological ionic model. *Discrete and Continuous Dynamical Systems - Series B*, 2019, 24 (9), pp.34. 10.3934/dcdsb.2019035 . hal-01680593

HAL Id: hal-01680593

<https://inria.hal.science/hal-01680593>

Submitted on 30 Oct 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **MATHEMATICAL ANALYSIS OF CARDIAC ELECTROMECHANICS WITH**
2 **PHYSIOLOGICAL IONIC MODEL**

3 MOSTAFA BENDAHMANE¹, FATIMA MROUE^{2,3}, MAZEN SAAD², AND RAAFAT TALHOUK³

ABSTRACT. This paper is concerned with the mathematical analysis of a coupled elliptic-parabolic system modeling the interaction between the propagation of electric potential coupled with general physiological ionic models and subsequent deformation of the cardiac tissue. A prototype system belonging to this class is provided by the electromechanical bidomain model, which is frequently used to study and simulate electrophysiological waves in cardiac tissue. The coupling between muscle contraction, biochemical reactions and electric activity is introduced with a so-called active strain decomposition framework, where the material gradient of deformation is split into an active (electrophysiology-dependent) part and an elastic (passive) one. We prove existence of weak solutions to the underlying coupled electromechanical bidomain model under the assumption of linearized elastic behavior and a truncation of the updated nonlinear diffusivities. The proof of the existence result, which constitutes the main thrust of this paper, is proved by means of a non-degenerate approximation system, the Faedo-Galerkin method, and the compactness method.

4 1. INTRODUCTION

5 The heart is the muscular organ that contracts to pump blood throughout the body. Failure
6 in its contraction leads to sudden cardiac death which is classified as the main cause of mortality
7 in the world. The contraction of the heart is initiated by an electrical signal called action poten-
8 tial starting in the sinoatrial node. The electrical signal then travels through the atria and the
9 ventricles. When the cardiac myocytes are electrically stimulated, the electrical potential inside
10 the cell changes: they depolarize. This fast depolarization allows the transmission of the electrical
11 signal through gap junctions and lateral junctions to the neighboring cells and their subsequent
12 contraction.

13
14 The goal of the present paper is to investigate the existence of solutions of a model describing
15 the interaction between the propagation of the action potential through the cardiac tissue and the
16 subsequent elastic mechanical response. The propagation of the electrical signal is described at
17 the macroscale by the bidomain model which is the most complete model used in numerical simu-
18 lations of the electrical activity of the heart [1]. It represents the averaged intra- and extracellular
19 potentials by a reaction-diffusion system of degenerate parabolic type. Its equations are derived
20 from the conservation of fluxes between the intra- and extracellular media separated by the cellular
21 membrane that acts as a capacitor. The conductivities in these two media reflect their anisotropic
22 properties. They are of different magnitude and they depend on the orientation of the cardiac
23 fibers. The equations of the bidomain model are coupled with phenomenological or physiological
24 ionic models. The bidomain system was proposed fourty years ago [1] and was extensively studied
25 from a well-posedness point of view in the last decade. A variational approach was first introduced
26 by Savaré and Franzone [2]. Later analyses took different directions: Bendahmane and Karlsen

Date: September 7, 2018.

2000 Mathematics Subject Classification. 74F99, 35K57, 92C10, 65M60.

Key words and phrases. Electro-mechanical coupling; Bidomain equations; Active deformation; Weak solutions; Weak compactness method.

¹Institut de mathématiques de Bordeaux (IMB) et l'institut de rythmologie et modélisation cardiaque (Liryc), université de Bordeaux et INRIA-Carmen Bordeaux Sud-Ouest

²Département de mathématiques, Centrale Nantes and Laboratoire de mathématiques Jean Leray

³Laboratoire de mathématiques, Ecole Doctorale des Sciences et Technologies, Université Libanaise, Hadat

1 used nondegenerate approximation systems to which they applied the Faedo-Galerkin scheme [3],
 2 Bourgault et al. introduced a “Bidomain” operator and used a semigroup approach [4], Matano
 3 and Mori derived global classical solutions [5] and Veneroni proved the existence and uniqueness
 4 of a strong solution with more involved ionic models using a fixed point approach with strong
 5 assumptions on the initial data [6].

6 Still at the macroscopic level, cardiac deformation can be modeled by the equations of motion
 7 for a hyperelastic material, written in the reference configuration. However, like any living tissue,
 8 there is a difficulty in applying the principles of force balance to cardiac tissue due to its ability to
 9 *actively* deform. In other words, its contraction is influenced by intrinsic mechanisms taking place
 10 at the microscopic level. This ability is taken into account in the literature following different
 11 approaches. One common option is to assume that stresses are additively decomposed into active
 12 and passive parts and it is called the active stress formulation ([7, 8, 9, 10, 11]). In this paper,
 13 we follow the active strain formulation, [12, 13], where the deformation gradient is factorized into
 14 active and passive factors, and fiber contraction rewrites in the mechanical balance of forces as
 15 a prescribed *active* deformation. Furthermore, this decomposition incorporates the micro-level
 16 information on fiber contraction and fiber directions in the kinematics [14]. These mechanisms
 17 essentially translate into a dependence of the strain energy function on auxiliary internal state
 18 variables, which represent the level of mechanical tissue activation passed across scales [15]. For
 19 comparisons between the two approaches in terms of numerical implementation, constitutive is-
 20 sues, and stability, we refer the reader to [16, 17].

21 Mathematical analysis of general nonlinear elasticity can be found in [18, 19], whereas applica-
 22 tions of those theories to the particular case of hyperelastic materials and cardiac mechanics are
 23 available in [9, 20, 21, 17, 22, 23]. Despite the large availability of references related to numerical
 24 methods and models for cardiac electromechanics (e.g [7, 8, 10, 24, 11]), there are open questions
 25 in their mathematical validity. To our knowledge, some existence results have been established by
 26 Pathmanatan *et al.* [25, 26] and Andreianov *et al.* [27]. Pathmanatan *et al.* analyzed a general
 27 model involving the active stress formulation where the activation depends on local stretch rate
 28 and derived constraints on the initial data. Andreianov *et al.* also assumed linearized elasticity
 29 equations but they adopted the active strain formulation and employed the bidomain model cou-
 30 pled with FitzHugh-Nagumo ionic model. This is the setting we employ in the present work, but
 31 we use a general physiological ionic model which kinetics overlap with Beeler-Reuter model [28] or
 32 Luo-Rudy model [29]. The electrical to mechanical coupling is obtained by considering that the
 33 active part of deformation incorporates the effect of calcium dynamics. We also consider that the
 34 evolution of electrical potential, governed by the bidomain equations, depends on the displacement
 35 which enters into the equations upon a change of coordinates from Eulerian to Lagrangian.

36 Putting our contributions into perspective, we first note that up to the author’s knowledge, exist-
 37 ence of solution of an electromechanical model coupled with physiological ionic model has never
 38 been rigorously mathematically analyzed. Moreover our paper admits a rigorous mathematical
 39 treatment, yielding the existence of weak solutions of our model. We point out that our model is
 40 degenerate, strongly nonlinear and so no maximum principle applies. We want to mention that
 41 we have not been able to prove uniqueness of weak solutions because of the presence of nonlinear
 42 lower-order terms in our model. Furthermore, comparing to the work [6] (where the author proves
 43 the existence of strong solutions without mechanics), here we give a different and constructive
 44 proof of the existence of weak solutions to the electromechanical bidomain model. Moreover, in
 45 comparison to the phenomenological ionic model used in [27], the physiological model considered
 46 herein contains a concentration variable z that appears as argument of a logarithm both in the
 47 dynamics of the concentration and in the ionic currents, and therefore it is necessary to bound z
 48 far from zero.

49 In the present work, we prove the existence of weak solutions to the coupled electromechanical
 50 problem by introducing non-degenerate approximation systems including an “artificial compress-
 51 ibility” condition. We prove existence of solutions to those approximation systems (for each fixed
 52 $\varepsilon > 0$) by applying the Faedo-Galerkin method, deriving a priori estimates, and then passing to
 53 the limit in the approximate solutions using compactness arguments. Having proved existence for
 54 the approximation systems, the goal is to send the regularization parameter ε to zero in sequences

1 of such solutions to fabricate weak solutions of the original systems. Again convergence is achieved
 2 by a priori estimates and compactness arguments. On the technical side, we point out that the
 3 passage to the limit in the pressure term is not straightforward due to the artificial compressibility
 4 assumption along with the use of “Navier-type” boundary conditions.

5 The contents of this paper are organized as follows. Section 2 describes the cardiac electromechanical
 6 model we adopt, presenting the equations of passive nonlinear mechanics, the bidomain
 7 system, and the active-strain-based coupling strategy. We also list the basic assumptions of the
 8 model and provide a definition of weak solution. In Section 3 we state and prove the solvability
 9 of the continuous problem employing Faedo-Galerkin approximations and compactness theory to
 10 obtain the existence of solution of a regularized problem in the first place. Then the existence of
 11 weak solutions for the original problem is given in Section 4 by using (one more time) a priori
 12 estimates and compactness arguments. In Section 5, we close our contribution with some remarks
 13 and discussion of future directions.

14 2. GOVERNING EQUATIONS FOR THE ELECTROMECHANICAL COUPLING

2.1. A general nonlinear elasticity problem. From the mechanical view point, we consider
 the heart as a homogeneous continuous material occupying in the initial undeformed configuration
 a bounded domain $\Omega_R \subset \mathbb{R}^d$ ($d = 3$) with Lipschitz continuous boundary $\partial\Omega_R$. Its deformation
 is described by the equations of motion written in the reference configuration Ω_R . The current
 configuration is the deformed configuration denoted by Ω . We look for the deformation field
 $\phi : \Omega_R \rightarrow \mathbb{R}^d$ that maps a material particle occupying initially the position \mathbf{X} to its current
 position $\mathbf{x} = \phi(\mathbf{X})$. We denote by $\mathbf{F} := \nabla_X \phi$, the deformation gradient tensor where ∇_X is the
 gradient operator with respect to the material coordinates \mathbf{X} , noting that $\det(\mathbf{F}) > 0$.

The cardiac tissue is also assumed to be a hyperelastic incompressible material. In other words,
 there exists a strain stored energy function $\mathcal{W} = \mathcal{W}(\mathbf{X}, \mathbf{F})$, differentiable with respect to \mathbf{F} , from
 which constitutive relations between strain and stresses are obtained. In addition, the first Piola
 stress tensor \mathbf{P} , which represents force per unit undeformed surface is given by:

$$\mathbf{P} = \frac{\partial \mathcal{W}}{\partial \mathbf{F}} - p \text{Cof}(\mathbf{F}),$$

where $\text{Cof}(\cdot)$ is the cofactor matrix, and p is the Lagrange multiplier associated to the incompressibility
 constraint: $\det(\mathbf{F}) = 1$ and interpreted as “hydrostatic pressure”. The balance equations
 in the reference configuration for deformations and pressure read as:

Find ϕ, p such that

$$\begin{aligned} \nabla \cdot \mathbf{P}(\mathbf{F}, p) &= \mathbf{g} \quad \text{in } \Omega_R, \\ \det(\mathbf{F}) &= 1 \quad \text{in } \Omega_R, \end{aligned} \tag{2.1}$$

15 completed with the Robin boundary condition

$$\mathbf{P}\mathbf{n} = -\alpha\phi \quad \text{on } \partial\Omega_R. \tag{2.2}$$

These are the steady state equations of motion to describe conservation of linear and angular
 momentum where \mathbf{g} is a prescribed body force, \mathbf{n} stands for the unit outward normal vector to
 $\partial\Omega_R$, and $\alpha > 0$ is a constant parameter. The choice of boundary conditions as (2.2) is due to
 the fact that they can be tuned to mimic the global motion of the cardiac muscle [15], unlike the
 unphysiological boundary treatment typically found in the literature, as using excessively rigid
 boundary conditions, or fixing the atrioventricular plane, or leaving the tissue completely free to
 move.

Clearly, in order to obtain a precise form of the first equation in (2.1), we need a particular
 constitutive relation defining \mathcal{W} . We consider herein the case of Neo-Hookean materials, where
 \mathcal{W} is defined by:

$$\mathcal{W} = \frac{1}{2} \mu \text{tr}[\mathbf{F}^T \mathbf{F} - \mathbf{I}],$$

16 with μ being the shear modulus. Hence, $\frac{\partial \mathcal{W}}{\partial \mathbf{F}} = \mu \mathbf{F}$ and $\mathbf{P} = \mu \mathbf{F} - p \text{Cof}(\mathbf{F})$. Although simplified,
 17 such a description of the passive response of the muscle features, so far, a nonlinear strain-stress

- 1 relationship arising from the incompressibility constraint. The forthcoming discussion will also
 2 reveal another form of strain-stress nonlinearity as a result of anisotropy inherited from the active
 3 strain incorporation. More involved models can be found in e.g. Refs. [9, 17, 15].

2.2. The bidomain equations. The electrophysiological aspect of the heart is incorporated in the model through the widely used bidomain equations [1]. The unknowns are the intracellular (i) and extracellular (e) electric potentials $v_i = v_i(t, \mathbf{x})$, $v_e = v_e(t, \mathbf{x})$ respectively, the transmembrane potential $v = v(t, \mathbf{x}) := v_i - v_e$, the gating or recovery variables $\mathbf{w} = \mathbf{w}(t, \mathbf{x}) = (w_1, \dots, w_k)$, and the concentration variable $z = z(t, \mathbf{x}) = (z_1, \dots, z_m)$ at $(t, \mathbf{x}) \in \Omega_T := (0, T) \times \Omega$, where T is the final time instant. Cardiac electrical conductivity is represented in the global coordinate system by the orthotropic tensors

$$\mathbf{K}_k(\mathbf{x}) = \sigma_k^l \mathbf{d}_l \otimes \mathbf{d}_l + \sigma_k^t \mathbf{d}_t \otimes \mathbf{d}_t + \sigma_k^n \mathbf{d}_n \otimes \mathbf{d}_n, \quad k \in \{e, i\},$$

where $\sigma_k^s = \sigma_k^s(\mathbf{x}) \in \mathbf{C}^1(\mathbb{R}^3)$, $k \in \{e, i\}$, $s \in \{l, t, n\}$, are the intra- and extracellular conductivities along, transversal, and normal to the fibers' direction, respectively. The direction of the fibers is a local quantity used to determine the principal directions of propagation, thus we have $\mathbf{d}_s = \mathbf{d}_s(\mathbf{x})$, $s \in \{l, t, n\}$. The externally applied stimulation currents corresponding to the intra- and extracellular spaces are represented by the functions I_s^i and I_s^e , respectively.

The bidomain equations are given by:

$$\begin{aligned} \chi c_m \partial_t v - \nabla \cdot (\mathbf{K}_i \nabla v_i) + \chi I_{\text{ion}}(v, \mathbf{w}, z) &= I_s^i & \text{in } \Omega_T, \\ \chi c_m \partial_t v + \nabla \cdot (\mathbf{K}_e \nabla v_e) + \chi I_{\text{ion}}(v, \mathbf{w}, z) &= I_s^e & \text{in } \Omega_T \\ \partial_t \mathbf{w} - \mathbf{R}(v, \mathbf{w}) &= 0 & \text{in } \Omega_T, \\ \partial_t z - G(v, \mathbf{w}, z) &= 0 & \text{in } \Omega_T, \end{aligned} \tag{2.3}$$

where $v = v_i - v_e$. Here c_m is the capacitance and χ is the membrane surface area per unit volume. For simplicity, we shall suppose that $\chi = 1$ and $c_m = 1$. Problem (2.3) is provided with homogeneous Neumann boundary conditions on the intra- and extracellular potentials. In the physiological membrane model, the ionic current I_{ion} has the following general form

$$I_{\text{ion}}(v, \mathbf{w}, z) := \sum_{i=1}^m d_i f_i(v) \prod_{j=1}^k w_j^{n_{i,j}} \left(v - r_i \log \left(\frac{z_e}{z_i} \right) \right).$$

Herein, d_i is the maximal conductance associated with the i^{th} current, f_i is a gating function depending on the transmembrane potential v , $n_{i,j}$ is positive integer and $E := r_i \log \left(\frac{z_e}{z_i} \right)$ is equilibrium (Nernst) potential (r_i is a constant and z_e is an extracellular concentration). Moreover, the dynamics of the gating variable \mathbf{w} is described in the Hodgkin-Huxley formalism by a system of ODEs governed by the following equation

$$\partial_t w_j = \alpha_j(v)(1 - w_j) - \beta_j(v)w_j$$

for $j = 1, \dots, k$. The functions α_j and β_j are positive with the following form

$$\frac{\rho_{1,\kappa} e^{\rho_{2,\kappa}(v-\bar{v})} + \rho_{3,\kappa}(v-\bar{v})}{1 + \rho_{4,\kappa} e^{\rho_{5,\kappa}(v-\bar{v})}},$$

- 4 where $\rho_{1,\kappa}, \rho_{3,\kappa}, \rho_{4,\kappa}, \bar{v} \geq 0$ and $\rho_{2,\kappa}, \rho_{5,\kappa} > 0$ are constants.
 5 The choice of the membrane model to be used is reflected in the functions $I_{\text{ion}}(v, \mathbf{w}, z)$, $\mathbf{R}(v, \mathbf{w})$ and
 6 $G(v, \mathbf{w}, z)$. For a physiological description of the action potential, we will consider a fairly general
 7 ionic model that corresponds for instance to the dynamics of Luo-Rudy model or Beeler-Reuter
 8 model [29, 28], given as in assumption (A.6) below.

2.3. The active strain model for the coupling of elasticity and bidomain equations.

The electrical to mechanical coupling is done through the ‘‘active strain model’’ [13] where the deformation gradient \mathbf{F} is factorized into a passive component \mathbf{F}_p and an active component \mathbf{F}_a , $\mathbf{F} = \mathbf{F}_p \mathbf{F}_a$. The tensor \mathbf{F}_p acts at the tissue level and accounts for both deformation of the material needed to insure compatibility and possible tension due to external loads. The tensor \mathbf{F}_a represents

the distortion that dictates deformation at the fiber level and depends on the electrophysiology through the relation, [14]:

$$\mathbf{F}_a = \mathbf{I} + \gamma_l \mathbf{d}_l \otimes \mathbf{d}_l + \gamma_t \mathbf{d}_t \otimes \mathbf{d}_t + \gamma_n \mathbf{d}_n \otimes \mathbf{d}_n$$

where γ_s , $s \in \{l, t, n\}$ are quantities that depend on the electrophysiology equations.

Such a factorization of the deformation tensor \mathbf{F} assumes the existence of an intermediate configuration between the reference and the current frames. In that configuration, the strain energy function depends solely on the deformation at the macroscale \mathbf{F}_p , [30]:

$$\mathcal{W} = \mathcal{W}(\mathbf{F}_p) = \mathcal{W}(\mathbf{F}\mathbf{F}_a^{-1}) = \frac{\mu}{2} \text{tr}[\mathbf{F}_p^T \mathbf{F}_p - \mathbf{I}] = \frac{\mu}{2} \text{tr}[\mathbf{F}_a^{-T} \mathbf{F}^T \mathbf{F} \mathbf{F}_a^{-1} - \mathbf{I}],$$

and the Piola stress tensor is given by :

$$\mathbf{P} = \mu \mathbf{F} \mathbf{C}_a^{-1} - p \text{Cof}(\mathbf{F})$$

- 1 where $\mathbf{C}_a^{-1} := \det(\mathbf{F}_a) \mathbf{F}_a^{-1} \mathbf{F}_a^{-T}$ (see also Refs. [14, 30]).
- 2 Further examining the expression of \mathbf{F}_a , we notice that mechanical activation is mainly influenced
- 3 by intracellular calcium release [24, 26, 31], and in particular, the dynamics of local strain follow
- 4 closely those of calcium release rather than those from the transmembrane potential, as reported
- 5 in Ref. [32]. Using a physiological ionic model, the aforementioned fact suggests that, ideally the
- 6 recovery variables \mathbf{w} and the concentration variable z approximate the spatio-temporal structure
- 7 of calcium. More physiologically-involved activation models require a dependence of γ_s not only
- 8 on calcium, but also on local stretch, local stretch rate, sliding velocity of crossbridges, and on
- 9 other force-length experimental relations [26, 15, 33], but for the sake of simplicity we restrict
- 10 ourselves to a phenomenological description of local activation in terms of the gating variables.
- 11 The scalar fields γ_l , γ_t and γ_n can be written as functions of a parameter γ :

$$\gamma_{l,t,n} = \gamma_{l,t,n}(\gamma), \quad (2.4)$$

where $\gamma_{l,t,n} : \mathbb{R} \mapsto [-\Gamma_{l,t,n}, 0]$ are Lipschitz continuous monotone functions. The values $\Gamma_{l,t,n}$ should be small enough, in order to ensure that $\det(\mathbf{F}_a)$ stays uniformly far from zero, for $\gamma \in \mathbb{R}$. The scalar field γ is the solution of the following ODE associated to the solution (v_i, v_e, w) of the bidomain system (2.3):

$$\partial_t \gamma - S(\gamma, \mathbf{w}) = 0 \quad \text{in } \Omega_T,$$

where $S(\gamma, \mathbf{w}) = \beta(\sum_{j=1}^k \eta_j w_j - \eta_0 \gamma)$, for positive physiological parameters β, η_j , $j = 0, 1, \dots, k$ (see Ref. [34]). Moreover, the functions $\gamma_{l,t,n}$ are assumed to be of the form:

$$\gamma_{l,t,n} = -\Gamma_{l,t,n} \frac{2}{\pi} \arctan(\gamma^+ / \gamma_R), \quad \text{where } \gamma_R \text{ is a reference value.}$$

Further details can be found in e.g. Refs. [35, 33].

The *mechanical-to-electrical* coupling is achieved by a change of variables in the bidomain equations from the current configuration (Eulerian coordinates) to the reference configuration (Lagrangian coordinates), which leads to a conduction term depending on the deformation gradient \mathbf{F} . Summarizing, the active strain formulation for the electromechanical activity in the heart is written as follows [30]:

$$\begin{aligned} -\nabla \cdot (a(\mathbf{x}, \gamma, \mathbf{F}, p)) &= \mathbf{g} && \text{in } \Omega_R, \\ \det(\mathbf{F}) &= 1 && \text{in } \Omega_R \text{ for a.e. } t \in (0, T), \\ \partial_t v + \nabla \cdot (\mathbf{M}_e(\mathbf{x}, \mathbf{F}) \nabla v_e) + I_{\text{ion}} &= I_s^e && \text{in } Q_T, \\ \partial_t v - \nabla \cdot (\mathbf{M}_i(\mathbf{x}, \mathbf{F}) \nabla v_i) + I_{\text{ion}} &= I_s^i && \text{in } Q_T, \\ v_i - v_e &= v && \text{in } Q_T, \\ \partial_t \mathbf{w} - \mathbf{R}(v, \mathbf{w}) &= 0 && \text{in } Q_T, \\ \partial_t z - G(v, \mathbf{w}, z) &= 0 && \text{in } Q_T, \\ \partial_t \gamma - S(\gamma, \mathbf{w}) &= 0 && \text{in } Q_T, \end{aligned} \quad (2.5)$$

1 where $Q_T := (0, T) \times \Omega_R$. Here, according to the above discussion, we should take

$$a(\mathbf{x}, \gamma, \mathbf{F}, p) := \mu \mathbf{F} \mathbf{C}_a^{-1}(\mathbf{x}, \gamma) - p \text{Cof}(\mathbf{F}), \quad (2.6)$$

2 and

$$\mathbf{M}_k(\mathbf{x}, \mathbf{F}) := (\mathbf{F})^{-1} \mathbf{K}_k(\mathbf{x})(\mathbf{F})^{-T}, \quad k \in \{i, e\} \quad (2.7)$$

3 The system of equations (2.5) has to be completed with suitable initial conditions for v, \mathbf{w}, γ, z
4 and with boundary conditions on $v_{i,e}$ and on the elastic flux $a(\cdot, \cdot, \cdot, \cdot)$.

5 **2.4. Linearizing the elasticity equations.** For the sake of simplicity of the mathematical anal-
6 ysis of the problem, the incompressibility condition $\det(\mathbf{F}) = 1$ and the flux in the equilibrium
7 equation are linearized. To linearize the determinant, we use:

$$\begin{aligned} \det(\mathbf{F}) &= \det(\mathbf{I}) + \frac{\partial(\det)}{\partial \mathbf{F}}(\mathbf{I})(\mathbf{F} - \mathbf{I}) + o(\mathbf{F} - \mathbf{I}) \\ &= 1 + \text{tr}(\mathbf{F} - \mathbf{I}) + o(\mathbf{F} - \mathbf{I}). \end{aligned}$$

But $\det(\mathbf{F}) = 1$, so one can use the approximation

$$\text{tr}(\mathbf{F} - \mathbf{I}) \simeq 0,$$

hence, $\nabla \cdot \boldsymbol{\phi} = \text{tr}(\mathbf{F}) \simeq \text{tr}(\mathbf{I}) = n$.

Now, when \mathbf{u} denotes the displacement i.e. $\mathbf{u} = \boldsymbol{\phi}(X) - X$, the above condition becomes $\nabla \cdot \mathbf{u} = 0$, which is the linearized incompressibility condition. We also linearize the flux in (2.6) with respect to \mathbf{F} using Taylor series' expansion of $\text{Cof}(\mathbf{F})$ about \mathbf{I} , given by:

$$\begin{aligned} \text{Cof}(\mathbf{F}) &= \text{Cof}(\mathbf{I}) + \frac{\partial \text{Cof}}{\partial \mathbf{F}}(\mathbf{I})(\mathbf{F} - \mathbf{I}) + o(\mathbf{F} - \mathbf{I}) \\ &= \mathbf{I} + \text{tr}(\mathbf{F} - \mathbf{I})\mathbf{I} - (\mathbf{F} - \mathbf{I})^T + o(\mathbf{F} - \mathbf{I}). \end{aligned}$$

8 and we obtain

$$a(\mathbf{x}, \gamma, \mathbf{F}, p) := \mu \mathbf{F} \mathbf{C}_a^{-1}(\mathbf{x}, \gamma) - p \mathbf{I}. \quad (2.8)$$

Introducing the notation $\sigma(\mathbf{x}, \gamma)$ for $\mu \mathbf{C}_a^{-1}(\mathbf{x}, \gamma)$, and using the displacement gradient $\nabla \mathbf{u}$ we rewrite the first equation of (2.5) as

$$-\nabla \cdot ((\mathbf{I} + \nabla \mathbf{u})\sigma(\mathbf{x}, \gamma)) + \nabla p = \mathbf{g},$$

then we reformulate the last equation to obtain a Stokes' like equation of the form:

$$-\nabla \cdot (\nabla \mathbf{u} \sigma(\mathbf{x}, \gamma)) + \nabla p = \mathbf{f}(t, \mathbf{x}, \gamma)$$

9 where

$$\mathbf{f}(t, \mathbf{x}, \gamma) = \nabla \cdot (\sigma(\mathbf{x}, \gamma)) + \mathbf{g}. \quad (2.9)$$

2.5. The problem to be solved and its weak formulation. For simplicity of notation, we will use Ω and Ω_T to denote Ω_R and Q_T respectively in all what follows, unless otherwise specified. Let us consider the following class of problems:

$$-\nabla \cdot (\nabla \mathbf{u} \sigma(\mathbf{x}, \gamma)) + \nabla p = \mathbf{f}(t, \mathbf{x}, \gamma), \quad \text{in } \Omega, \text{ for a.e. } t \in (0, T), \quad (2.10)$$

$$\nabla \cdot \mathbf{u} = 0 \quad \text{in } \Omega, \text{ for a.e. } t \in (0, T), \quad (2.11)$$

$$\partial_t v - \nabla \cdot (\mathbf{M}_i(\mathbf{x}, \nabla \mathbf{u}) \nabla v_i) + I_{\text{ion}}(v, \mathbf{w}, z) = I_s^i(t, \mathbf{x}) \quad \text{in } \Omega_T, \quad (2.12)$$

$$\partial_t v + \nabla \cdot (\mathbf{M}_e(\mathbf{x}, \nabla \mathbf{u}) \nabla v_e) + I_{\text{ion}}(v, \mathbf{w}, z) = I_s^e(t, \mathbf{x}) \quad \text{in } \Omega_T, \quad (2.13)$$

$$v = v_i - v_e \quad \text{in } \Omega_T, \quad (2.14)$$

$$\partial_t \mathbf{w} = \mathbf{R}(v, \mathbf{w}, z) \quad \text{in } \Omega_T, \quad (2.15)$$

$$\partial_t z = G(v, \mathbf{w}, z) \quad \text{in } \Omega_T, \quad (2.16)$$

$$\partial_t \gamma = S(\gamma, \mathbf{w}) \quad \text{in } \Omega_T. \quad (2.17)$$

10 Equations (2.10),(2.12),(2.13) are complemented with the boundary data (including the lineariza-
11 tion of (2.2)):

$$\nabla \mathbf{u} \sigma(\mathbf{x}, \gamma) \mathbf{n} - p \mathbf{n} = -\alpha \mathbf{u} \quad \text{on } \partial \Omega, \text{ for a.e. } t \in (0, T) \quad (2.18)$$

1 for some $\alpha > 0$ and

$$(\mathbf{M}_k(\mathbf{x}, \nabla \mathbf{u}) \nabla v_k) \cdot \mathbf{n} = 0 \quad \text{on } (0, T) \times \partial\Omega, \quad k = i, e \quad (2.19)$$

2 (different boundary conditions can be imposed on $v_{i,e}$; the choice of Neumann conditions (2.19)
3 results in the compatibility constraint (2.31) below). The initial data are:

$$v(0, \cdot) = v_0, \quad \mathbf{w}(0, \cdot) = \mathbf{w}_0, \quad z(0, \cdot) = z_0, \quad \gamma(0, \cdot) = \gamma_0 \quad \text{in } \Omega. \quad (2.20)$$

4 For simplicity we take $m = 1$ in the concentration variable z . The following properties of the
5 model (2.10)–(2.17) and (2.18)–(2.20) are instrumental for the subsequent analysis:

(A.1) $(\sigma(\mathbf{x}, \gamma))_{\mathbf{x} \in \Omega, \gamma \in \mathbb{R}}$ is a family of symmetric tensors, uniformly bounded and positive definite:

$$\exists c > 0 : \text{ for a.e. } \mathbf{x} \in \Omega, \forall \gamma \in \mathbb{R} \quad \forall \mathbf{M} \in \mathbb{M}_{3 \times 3} \quad \frac{1}{c} |\mathbf{M}|^2 \leq (\sigma(\mathbf{x}, \gamma) \mathbf{M}) : \mathbf{M} \leq c |\mathbf{M}|^2;$$

6 (A.2) the function $\sigma(\cdot, \cdot)$ is in $C^1(\bar{\Omega} \times \mathbb{R})$;

(A.3) $(\mathbf{M}_{i,e}(\mathbf{x}, \mathbf{M}))_{\mathbf{x} \in \Omega, \mathbf{M} \in \mathbb{M}_{3 \times 3}}$ is a family of symmetric matrices, uniformly bounded and positive definite:

$$\exists c > 0 : \text{ for a.e. } \mathbf{x} \in \Omega, \forall \mathbf{M} \in \mathbb{M}_{3 \times 3} \quad \forall \xi \in \mathbb{R}^3 \quad \frac{1}{c} |\xi|^2 \leq (\mathbf{M}_{i,e}(\mathbf{x}, \mathbf{M}) \xi) \cdot \xi \leq c |\xi|^2;$$

7 (A.4) the maps $\mathbf{M} \mapsto \mathbf{M}_{i,e}(\cdot, \mathbf{M})$ are uniformly Lipschitz continuous;

8 (A.5) the function S is given by $S(\gamma, \mathbf{w}) = \beta(\sum_{j=1}^k \eta_j w_j - \eta_0 \gamma)$, for positive physiological pa-
9 rameters $\beta, \eta_j, j = 0, 1, \dots, k$;

(A.6) the functions \mathbf{R}, G and I_{ion} are given by the kinetics of a general physiological ionic model and it can be verified that the assumptions, stated below, are satisfied by several gating and ionic concentration variables in Beeler-Reuter or Luo-Rudy ionic models. We assume that the function $\mathbf{R}(v, \mathbf{w}) := (R_1(v, w_1), \dots, R_k(v, w_k))$ where $R_j : \mathbb{R}^2 \rightarrow \mathbb{R}$ are locally Lipschitz continuous functions defined by

$$R_j(v, \mathbf{w}) = \alpha_j(v)(1 - w_j) - \beta_j(v)w_j$$

10 where α_j and $\beta_j, j = 1, \dots, k$ are positive rational functions of exponentials in v such
11 that:

$$\begin{aligned} 0 < \alpha_j(v), \beta_j(v) &\leq C_{\alpha, \beta}(1 + |v|), \\ \frac{d\alpha_j}{dv} \text{ and } \frac{d\beta_j}{dv} &\text{ are uniformly bounded,} \end{aligned} \quad (2.21)$$

12 for some constant $C_{\alpha, \beta} > 0$. The function $I_{\text{ion}} : \mathbb{R} \times \mathbb{R}^k \times (0, +\infty) \rightarrow \mathbb{R}$ has the general
13 form:

$$I_{\text{ion}}(v, \mathbf{w}, z) = \sum_{j=1}^k I_{\text{ion}}^j(v, w_j) + I_{\text{ion}}^z(v, \mathbf{w}, z, \ln z) \quad (2.22)$$

14 where $I_{\text{ion}}^j \in C^0(\mathbb{R} \times \mathbb{R}^k)$ and satisfies the condition:

$$|I_{\text{ion}}^j(v, w_j)| \leq C_{1,I}(1 + |w_j| + |v|), \quad (2.23)$$

15 and I_{ion}^z is such that:

$$\begin{aligned} I_{\text{ion}}^z &\in C^1(\mathbb{R} \times \mathbb{R}^k \times \mathbb{R}^+ \times \mathbb{R}), \\ I_{\text{ion}}^z(v, \mathbf{w}, z, \ln z) &\leq C_{2,I}(1 + |v| + |w| + |z| + \ln z), \end{aligned} \quad (2.24)$$

$$I_{\text{ion}}^z(v, \mathbf{w}, z, \ln z) \geq C_{3,I} \sum_{j=1}^k (|v| + w_j + w_j \ln z), \quad (2.25)$$

$$0 < \underline{\Theta}(\mathbf{w}) \leq \frac{\partial}{\partial \zeta} I_{\text{ion}}^z(v, \mathbf{w}, z, \zeta) \leq \bar{\Theta}(\mathbf{w}), \quad (2.26)$$

$$\left| \frac{\partial}{\partial v} I_{\text{ion}}^z(v, \mathbf{w}, z, \zeta) \right| \leq L(\mathbf{w}), \quad (2.27)$$

$$\frac{\partial}{\partial w_j} I_{\text{ion}}^z \leq C_{4,I}(1 + |v| + |\ln z|), \quad \forall j = 1, \dots, k, \quad (2.28)$$

$$0 \leq \frac{\partial}{\partial z} I_{\text{ion}}^z \leq C_{5,I}, \quad (2.29)$$

1 where $\underline{\Theta}, \bar{\Theta}, L$ belong to $C^0(\mathbb{R}, \mathbb{R}^+)$ and $C_{1,I}, \dots, C_{5,I}$ are positive constants. Finally the
2 function G is given by:

$$G(v, \mathbf{w}, z) = a_1(a_2 - z) - a_3 I_{\text{ion}}^z(v, \mathbf{w}, z, \ln z), \quad (2.30)$$

3 where a_1, a_2, a_3 are positive physiological constants that vary from one ion to another. In
4 our case, we only consider z to correspond to the intracellular calcium concentration.

5 **(A.7)** The following condition holds

$$\int_{\Omega} I_s^i = \int_{\Omega} I_s^e \text{ and } \int_{\Omega} v_e(\mathbf{x}, t) \, d\mathbf{x} = 0 \text{ for a.e. } t \in (0, T). \quad (2.31)$$

6 **(A.8)** The data v_0, w_0, γ_0, z_0 lie in $H^1(\Omega)$ with $z_0 \geq c_0 > 0$ (c_0 is a positive constant) whereas
7 $\mathbf{g} \in L^2(\Omega_T)^3$ (recall definition (2.9)), and $I_s^{i,e} \in L^2(\Omega_T)$.

8 Note that, in practice, one starts with an undeformed configuration, i.e., with $\gamma \equiv 0$. Observe also
9 that the above system (2.5), (2.11) with $a(\cdot, \cdot, \cdot, \cdot)$ and $\mathbf{M}_{i,e}(\cdot, \cdot)$ given by (2.8), (2.7) falls within
10 the framework described by (2.10)–(2.20) and **(A.1)**–**(A.8)**. Indeed, it is enough to check that
11 assumptions **(A.1)**–**(A.4)** are satisfied (assumptions **(A.5)**–**(A.8)** are already enforced). Let us
12 stress that due to assertion (2.4), properties **(A.1)**, **(A.2)** hold. Thanks to properties **(A.1)**–**(A.8)**,
13 the following weak formulation makes sense.

14 **Definition 2.1.** A weak solution of problem (2.10)–(2.20) is $U = (\mathbf{u}, p, v_i, v_e, v, \mathbf{w}, \gamma, z)$ such
15 that:

- 16 (i) $\mathbf{u} \in L^2(0, T; H^1(\Omega)^3)$, $p \in L^2(\Omega_T)$, $v_i \in L^2(0, T; H^1(\Omega))$;
17 $v_e \in L^2(0, T; H^{1,0}(\Omega))$ where $H^{1,0}(\Omega) := \{v_e \in H^1(\Omega) \text{ such that } \int_{\Omega} v_e \, d\mathbf{x} = 0\}$;
18 $v \in E := L^2(0, T; H^1(\Omega))$ with $\partial_t v \in E' := L^2(0, T; (H^1(\Omega))')$;
19 $\gamma, z \in C([0, T]; L^2(\Omega))$ and $\mathbf{w} \in C([0, T]; L^2(\Omega)^k)$;
20 $z(t, x) > 0$ and $0 \leq w_j(t, x) \leq 1$ for a.e. $(t, x) \in \Omega_T$ and for $j = 1, \dots, k$;
21 (ii) For a.e. $t \in (0, T)$, for all $\mathbf{v} \in H^1(\Omega)^3$ there holds:

$$\int_{\Omega} (\nabla \mathbf{u} \sigma(\mathbf{x}, \gamma) : \nabla \mathbf{v} - p \nabla \cdot \mathbf{v}) \, d\mathbf{x} = \int_{\Omega} \mathbf{f} \cdot \mathbf{v} \, d\mathbf{x} - \int_{\partial\Omega} \alpha \mathbf{u} \cdot \mathbf{v} \, ds \quad (2.32)$$

22 (in the last integral, \mathbf{u}, \mathbf{v} are shortcuts for the traces of \mathbf{u}, \mathbf{v} on $\partial\Omega$).

23 For all $q \in L^2(\Omega)$

$$\int_{\Omega} q(\nabla \cdot \mathbf{u}) \, d\mathbf{x} = 0. \quad (2.33)$$

- (iii) For a.e. $t \in (0, T)$, for all $\xi \in H^1(\Omega)$, $\mu \in H^{1,0}(\Omega)$, there holds

$$\langle \partial_t v, \xi \rangle + \int_{\Omega} (\mathbf{M}_i(\mathbf{x}, \nabla \mathbf{u}) \nabla v_i \cdot \nabla \xi + I_{\text{ion}}(v, \mathbf{w}, z) \xi) = \int_{\Omega} I_s^i \xi, \quad (2.34)$$

$$\langle \partial_t v, \mu \rangle - \int_{\Omega} (\mathbf{M}_e(\mathbf{x}, \nabla \mathbf{u}) \nabla v_e \cdot \nabla \mu + I_{\text{ion}}(v, \mathbf{w}, z) \mu) = \int_{\Omega} I_s^e \mu, \quad (2.35)$$

24 with $v = v_i - v_e$ a.e. in Ω_T and $v(0, \cdot) = v_0$ a.e. in Ω .

- 25 (iv) For a.e. $t \in (0, T)$ the equations (2.15), (2.17), (2.16) are fulfilled in $L^2(\Omega)$, and $\mathbf{w}(0, \cdot) =$
26 \mathbf{w}_0 , $\gamma(0, \cdot) = \gamma_0$, $z(0, \cdot) = z_0$ a.e. in Ω .

27 Our main result in this paper is the following theorem:

1 **Theorem 2.1.** Assume that conditions (A.1)–(A.8) hold. If $v_0 \in L^2(\Omega)$, $\mathbf{w}_0 \in H^1(\Omega)^k$, γ_0 ,
 2 $z_0 \in H^1(\Omega)$, with $z_0 \geq c_0 > 0$, $\mathbf{g} \in L^2(\Omega_T)^3$, $I_s^{i,e} \in L^2(\Omega_T)$ then there exists a weak solution
 3 $U = (\mathbf{u}, p, v_i, v_e, v, \mathbf{w}, \gamma, z)$ to (2.10)–(2.17) with the boundary and initial data specified as in
 4 (2.18)–(2.20).

5 **Remark 2.1.** In definition 2.1, the integrals are well defined since the tensors $\boldsymbol{\sigma}$ and $\mathbf{M}_{i,e}$ are
 6 uniformly bounded and the functions $\mathbf{u}(t, \cdot)$, $v_{i,e}(t, \cdot)$ are in $H^1(\Omega)^3$ and $H^1(\Omega)$ respectively.
 7 We also note that passage to the limit in the pressure term p is not straightforward because it is
 8 not possible to establish an a priori uniform estimate in $L^2(\Omega_T)$ due to the use of the “artificial
 9 compressibility” which utility becomes clearer in the following section.

10

3. EXISTENCE FOR A REGULARIZED PROBLEM

11 The proof of existence of solutions is introduced in this section using a Faedo-Galerkin method
 12 in space. A parabolic regularization similar to the one in [3] is used to ensure existence of Faedo-
 13 Galerkin solutions. A priori estimates are obtained on the Faedo-Galerkin solutions followed
 14 by compactness results to secure their convergence towards a weak solution of the regularized
 15 problem.

16 **3.1. Faedo-Galerkin approximations for the regularized problem.** We use classical Hilbert
 17 bases orthonormal in $L^2(\Omega)$ and orthogonal in $H^1(\Omega)$, denoted by $(\boldsymbol{\psi}_l)_{l \in \mathbb{N}}$ and $(\omega_l)_{l \in \mathbb{N}}$ such that
 18 $\text{span}(\boldsymbol{\psi}_l)_{l \in \mathbb{N}}$ is dense in $L^2(\Omega)^3$ and $H^1(\Omega)^3$, and $\text{span}(\omega_l)_{l \in \mathbb{N}}$ is dense in $L^2(\Omega)$ and $H^1(\Omega)$ (see
 19 for example [36]).

In order to impose the compatibility condition (2.31), we let

$$\mu_l = \omega_l - \frac{1}{|\Omega|} \int_{\Omega} \omega_l d\mathbf{x}, \text{ so that } \int_{\Omega} \mu_l d\mathbf{x} = 0.$$

20 We observe that $\text{span}\{\mu_l\}_{l \in \mathbb{N}}$ is dense in the space $H^{1,0}(\Omega)$, given as in Definition 2.1. Fur-
 21 thermore, we orthonormalize the basis $(\mu_l)_{l \in \mathbb{N}}$ by the Gram-Schmidt process, and we denote the
 22 new basis by $(\boldsymbol{\mu}_l)_{l \in \mathbb{N}}$ that is orthonormal in $L^2(\Omega)$. For $m \geq 0$, we introduce the finite di-
 23 mensional spaces $\mathbf{H}_m = \text{span}\{\boldsymbol{\psi}_0, \dots, \boldsymbol{\psi}_m\} \subset H^1(\Omega)^3$, $L_m = \text{span}\{\mu_0, \dots, \mu_m\} \subset H^{1,0}(\Omega)$ and
 24 $W_m = \text{span}\{\omega_0, \dots, \omega_m\} \subset H^1(\Omega)$.

25

26 We are looking for a discrete solution $\mathbf{u}_m = (\mathbf{u}_{\varepsilon,m}, p_{\varepsilon,m}, v_m, v_{i,\varepsilon,m}, v_{e,\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m}, \gamma_{\varepsilon,m})$ (for
 27 fixed $\varepsilon > 0$) of the system (3.2) below with

$$\begin{aligned} \mathbf{u}_m &= \sum_{l=0}^m \mathbf{u}_{l,m} \boldsymbol{\psi}_l, & p_m &= \sum_{l=0}^m p_{l,m} \omega_l & v_{i,m} &= \sum_{l=0}^m v_{i,l,m} \omega_l, \\ v_{e,m} &= \sum_{l=0}^m v_{e,l,m} \mu_l, & v_m &= v_{i,m} - v_{e,m}, & \gamma_m &= \sum_{l=0}^m \gamma_{l,m} \omega_l, \\ w_{j,m} &= \sum_{l=0}^m w_{j,l,m} \omega_l, & \forall j &= 1, \dots, k, & z_m &= \sum_{l=0}^m z_{l,m} \omega_l. \end{aligned} \quad (3.1)$$

28 Upon discretization, we obtain a system of ODEs coupled to a system of algebraic equations to
 29 be solved at every time t . Hence, the existence of the discrete solution is not obvious and only
 30 the ODE part of the system satisfies the conditions of Cauchy-Lipschitz' theorem. So we resort
 31 to a time regularization of the Faedo-Galerkin discretization in the spirit of [3]. We obtain the

1 following regularized system

$$\begin{aligned}
\varepsilon \frac{d}{dt} \int_{\Omega} \mathbf{u}_{\varepsilon,m} \cdot \boldsymbol{\psi}_l + \int_{\Omega} (\nabla \mathbf{u}_{\varepsilon,m}) \boldsymbol{\sigma}(\mathbf{x}, \gamma_{\varepsilon,m}) : \nabla \boldsymbol{\psi}_l - p_{\varepsilon,m} \nabla \cdot \boldsymbol{\psi}_l \, d\mathbf{x} \\
+ \int_{\partial\Omega} \alpha \mathbf{u}_{\varepsilon,m} \cdot \boldsymbol{\psi}_l \, ds = \int_{\Omega} \mathbf{f} \cdot \boldsymbol{\psi}_l \, d\mathbf{x}, \\
\varepsilon \frac{d}{dt} \int_{\Omega} p_{\varepsilon,m} \cdot \omega_l + \int_{\Omega} \omega_l \nabla \cdot \mathbf{u}_{\varepsilon,m} = 0, \\
\frac{d}{dt} \int_{\Omega} v_{\varepsilon,m} \omega_l + \varepsilon \frac{d}{dt} \int_{\Omega} v_{i,\varepsilon,m} \omega_l + \int_{\Omega} (\mathbf{M}_i(\mathbf{x}, \nabla \mathbf{u}_{\varepsilon,m}) \nabla v_{i,\varepsilon,m} \cdot \nabla \omega_l \\
+ I_{\text{ion}}(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m}) \omega_l) \, d\mathbf{x} = \int_{\Omega} I_s^i \omega_l \, d\mathbf{x}, \\
\frac{d}{dt} \int_{\Omega} v_{\varepsilon,m} \mu_l - \varepsilon \frac{d}{dt} \int_{\Omega} v_{e,\varepsilon,m} \mu_l - \int_{\Omega} (\mathbf{M}_e(\mathbf{x}, \nabla \mathbf{u}_{\varepsilon,m}) \nabla v_{e,\varepsilon,m} \cdot \nabla \mu_l \\
+ I_{\text{ion}}(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m}) \mu_l) \, d\mathbf{x} = \int_{\Omega} I_s^e \mu_l \, d\mathbf{x}, \\
\frac{d}{dt} \int_{\Omega} w_{j,\varepsilon,m} \omega_l = \int_{\Omega} R_j(v_{\varepsilon,m}, w_{j,\varepsilon,m}) \omega_l, \\
\frac{d}{dt} \int_{\Omega} z_{\varepsilon,m} \omega_l = \int_{\Omega} G(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m}) \omega_l, \\
\frac{d}{dt} \int_{\Omega} \gamma_{\varepsilon,m} \omega_l = \int_{\Omega} S(\gamma_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}) \omega_l,
\end{aligned} \tag{3.2}$$

2 for $l = 0, \dots, m$. Having no initial conditions on the functions \mathbf{u} , p , v_i and v_e in the original
3 problem, we need to supplement our system with initial conditions. We define the functions:

$$\begin{aligned}
v_{i,0} &= \frac{v_0}{2} + \frac{1}{|\Omega|} \int_{\Omega} \frac{v_0}{2} \, d\mathbf{x}, \\
v_{e,0} &= -\frac{v_0}{2} + \frac{1}{|\Omega|} \int_{\Omega} \frac{v_0}{2} \, d\mathbf{x},
\end{aligned}$$

4 so that $v_0 = v_{i,0} - v_{e,0}$ and $\int_{\Omega} v_{e,0} \, d\mathbf{x} = 0$. We further select $\mathbf{u}_0 = 0$ and an arbitrary p_0 . The
5 initial data of the ODE system are then given by

$$\begin{aligned}
\mathbf{u}_{\varepsilon,m}(0) &= 0, & p_{\varepsilon,m}(0) &= \sum_{l=0}^m p_{0,l,m} \omega_l, \quad \text{where } p_{0,l,m} = \langle p_0, \omega_l \rangle_{L^2}, \\
v_{i,\varepsilon,m}(0) &= \sum_{l=0}^m v_{i,0,l,m} \omega_l, & & \text{where } v_{i,0,l,m} = \langle v_{i,0}, \omega_l \rangle_{L^2}, \\
v_{e,\varepsilon,m}(0) &= \sum_{l=0}^m v_{e,0,l,m} \mu_l, & & \text{where } v_{e,0,l,m} = \langle v_{e,0}, \mu_l \rangle_{L^2}, \\
w_{j,\varepsilon,m}(0) &= \sum_{l=0}^m w_{j,0,l,m} \omega_l, & & \text{where } w_{j,0,l,m} = \langle w_{j,0}, \omega_l \rangle_{L^2} \\
z_{\varepsilon,m}(0) &= \sum_{l=1}^m z_{0,l,m} \omega_l & & \text{where } z_{0,l,m} = \langle z_0, \omega_l \rangle_{L^2} \\
\gamma_{\varepsilon,m}(0) &= \sum_{l=0}^m \gamma_{0,l,m} \omega_l & & \text{where } \gamma_{0,l,m} = \langle \gamma_0, \omega_l \rangle_{L^2},
\end{aligned} \tag{3.3}$$

for $j = 1, \dots, k$. Using the orthonormality of the bases, we can write (3.2) as a system of ordinary differential equations in the coefficients:

$$\left\{ \{\mathbf{u}_{l,m}\}_{l=0}^m, \{p_{l,m}\}_{l=0}^m, \{v_{i,l,m}\}_{l=0}^m, \{v_{e,l,m}\}_{l=0}^m, \{\mathbf{w}_{l,m}\}_{l=0}^m, \{\gamma_{l,m}\}_{l=0}^m, \{z_{l,m}\}_{l=0}^m \right\}.$$

- 1 To be concise, we detail in the following paragraph how the bidomain equations can be treated to
 2 obtain the ODE system. We first note that using $v_m = v_{i,m} - v_{e,m}$, we have:

$$\begin{aligned} \frac{d}{dt} \int_{\Omega} v_{i,\varepsilon,m} \omega_l - \frac{d}{dt} \int_{\Omega} v_{e,\varepsilon,m} \omega_l + \varepsilon \frac{d}{dt} \int_{\Omega} v_{i,\varepsilon,m} \omega_l + \int_{\Omega} (\mathbf{M}_i(\mathbf{x}, \nabla \mathbf{u}_{\varepsilon,m}) \nabla v_{i,\varepsilon,m} \cdot \nabla \omega_l \quad (3.4) \\ + I_{\text{ion}}(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m}) \omega_l) d\mathbf{x} = \int_{\Omega} I_s^i \omega_l d\mathbf{x}, \end{aligned}$$

$$\begin{aligned} \frac{d}{dt} \int_{\Omega} v_{i,\varepsilon,m} \mu_l - \frac{d}{dt} \int_{\Omega} v_{e,\varepsilon,m} \mu_l - \varepsilon \frac{d}{dt} \int_{\Omega} v_{e,\varepsilon,m} \mu_l - \int_{\Omega} (\mathbf{M}_e(\mathbf{x}, \nabla \mathbf{u}_{\varepsilon,m}) \nabla v_{e,\varepsilon,m} \cdot \nabla \mu_l \quad (3.5) \\ + I_{\text{ion}}(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m}) \mu_l) d\mathbf{x} = \int_{\Omega} I_s^e \mu_l d\mathbf{x}, \end{aligned}$$

- 3 Replacing $v_{i,\varepsilon,m}$ and $v_{e,\varepsilon,m}$ by their expressions as in (3.1), we obtain for $l = 0, \dots, m$:

$$\begin{aligned} (1 + \varepsilon) \sum_{r=0}^m v'_{i,r,m} \int_{\Omega} \omega_r \omega_l - \sum_{r=0}^m v'_{e,r,m} \int_{\Omega} \mu_r \omega_l + \int_{\Omega} (\mathbf{M}_i(\mathbf{x}, \nabla \mathbf{u}_{\varepsilon,m}) \nabla v_{i,\varepsilon,m} \cdot \nabla \omega_l \\ + I_{\text{ion}}(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m}) \omega_l) d\mathbf{x} = \int_{\Omega} I_s^i \omega_l d\mathbf{x}, \\ \sum_{r=0}^m v'_{i,r,m} \int_{\Omega} \omega_r \mu_l - (1 + \varepsilon) \sum_{r=0}^m v'_{e,r,m} \int_{\Omega} \mu_r \mu_l - \int_{\Omega} (\mathbf{M}_e(\mathbf{x}, \nabla \mathbf{u}_{\varepsilon,m}) \nabla v_{e,\varepsilon,m} \cdot \nabla \mu_l \\ + I_{\text{ion}}(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m}) \mu_l) d\mathbf{x} = \int_{\Omega} I_s^e \mu_l d\mathbf{x}, \end{aligned}$$

- 4 By the L^2 -orthonormality of the bases, the above equations can be rewritten in the form:

$$\begin{aligned} (1 + \varepsilon) v'_{i,r,m} - \sum_{r=0}^m \left(\int_{\Omega} \mu_r \omega_l \right) v'_{e,r,m} = F_i \left(\{\mathbf{u}_{l,m}\}_{r=0}^m, \{v_{i,r,m}\}_{r=0}^m, \{v_{e,r,m}\}_{r=0}^m, \{\mathbf{w}_{r,m}\}_{r=0}^m, \{z_{r,m}\}_{r=0}^m \right), \\ - \sum_{r=0}^m v'_{i,r,m} \int_{\Omega} \omega_r \mu_l + (1 + \varepsilon) v'_{e,l,m} = F_e \left(\{\mathbf{u}_{l,m}\}_{r=0}^m, \{v_{i,r,m}\}_{r=0}^m, \{v_{e,r,m}\}_{r=0}^m, \{\mathbf{w}_{r,m}\}_{r=0}^m, \{z_{r,m}\}_{r=0}^m \right), \end{aligned}$$

where F_k , $k = i, e$ assemble all the terms not containing time derivatives. The latter system is equivalent to a system written as:

$$\mathbf{M} \begin{pmatrix} v'_{i,m} \\ v'_{e,m} \end{pmatrix} = b,$$

where

$$\mathbf{M} = \begin{pmatrix} (1 + \varepsilon) \mathbf{I}_{m+1} & -\mathbf{A} \\ -\mathbf{A}^T & (1 + \varepsilon) \mathbf{I}_{m+1} \end{pmatrix},$$

and $\mathbf{A} = (a_{lr})$ with $a_{lr} = \int_{\Omega} \omega_l \mu_r$. In order to write: $\begin{pmatrix} v'_{i,m} \\ v'_{e,m} \end{pmatrix} = \mathbf{M}^{-1} b$, we need to prove that the matrix \mathbf{M} is invertible. For this sake, we expand it as:

$$\mathbf{M} = \begin{bmatrix} \mathbf{I}_{m+1} & -\mathbf{A} \\ -\mathbf{A}^T & \mathbf{I}_{m+1} \end{bmatrix} + \varepsilon \begin{bmatrix} \mathbf{I}_{m+1} & 0 \\ 0 & \mathbf{I}_{m+1} \end{bmatrix}.$$

It is enough to prove that the matrix $\mathbf{N} := \begin{bmatrix} \mathbf{I}_{m+1} & -\mathbf{A} \\ -\mathbf{A}^T & \mathbf{I}_{m+1} \end{bmatrix}$ is positive.

Let $\xi = \begin{pmatrix} \xi_i \\ \xi_e \end{pmatrix}$, where $\xi_i = (\xi_{i,0}, \dots, \xi_{i,m})^T \in \mathbb{R}^{m+1}$ and $\xi_e = (\xi_{e,0}, \dots, \xi_{e,m})^T \in \mathbb{R}^{m+1}$. Then

$$\xi^T \mathbf{N} \xi = \xi_i^T \xi_i - \xi_i^T \mathbf{A} \xi_e + \xi_e^T \xi_e - \xi_e^T \mathbf{A}^T \xi_i$$

So we have

$$\begin{aligned}
\xi^T \mathbf{N} \xi &= \sum_{k,l} \left[\xi_{i,k} \xi_{i,l} \int_{\Omega} \omega_k \omega_l - 2 \xi_{i,k} a_{kl} \xi_{e,l} + \xi_{e,k} \xi_{e,l} \int_{\Omega} \mu_k \mu_l \right] \\
&= \int_{\Omega} \sum_{k,l} [\xi_{i,k} \xi_{i,l} \omega_k \omega_l - 2 \xi_{i,k} \xi_{e,l} \omega_l \mu_k + \xi_{e,k} \xi_{e,l} \mu_k \mu_l] \\
&= \int_{\Omega} \left(\sum_l \xi_{i,l} \omega_l \right)^2 - 2 \sum_{k,l} \xi_{i,k} \xi_{e,l} \omega_l \mu_k + \left(\sum_l \xi_{e,l} \mu_l \right)^2 \\
&= \int_{\Omega} \left[\sum_l \xi_{i,l} \omega_l - \sum_l \xi_{e,l} \mu_l \right]^2 \geq 0.
\end{aligned}$$

1 Thus the matrix \mathbf{M} is positive definite, hence invertible. Consequently, the whole system (3.2)
2 can be written as a system of ordinary differential equations in the form $y'(t) = f(t, y(t))$.

3

4 To prove existence of a local solution to the obtained ODE system, we note that by virtue of
5 assumptions (A.1)-(A.8), the functions on the right hand side of the system are Carathéodory
6 functions bounded by L^1 functions. According to classical ODE theory, the system admits a local in
7 time unique solution and the functions defined by (3.1) are well-defined and constitute approximate
8 solutions to the regularized system (3.2). The global existence of the Faedo-Galerkin solutions is a
9 consequence of the m -independent a priori estimates on $\mathbf{u}_{\varepsilon,m}$, $p_{\varepsilon,m}$, $v_{\varepsilon,m}$, $v_{i,\varepsilon,m}$, $v_{e,\varepsilon,m}$, $\mathbf{w}_{\varepsilon,m}$, $\gamma_{\varepsilon,m}$
10 and $z_{\varepsilon,m}$ that are derived in the next section. For more details, consult [3].

11 **3.2. A priori estimates.** To prove global existence of the Faedo-Galerkin solutions we derive
12 m -independent a priori estimates bounding $v_{\varepsilon,m}$, $v_{i,\varepsilon,m}$, $v_{e,\varepsilon,m}$, $\mathbf{u}_{\varepsilon,m}$, $p_{\varepsilon,m}$, $\mathbf{w}_{j,\varepsilon,m}$, $z_{\varepsilon,m}$
13 and $\gamma_{\varepsilon,m}$ in various Banach spaces. Given some (absolutely continuous) coefficients $a_{l,m}(t)$,
14 $c_{l,m}(t)$, $b_{k,l,m}(t)$, $k = i, e$, and $d_{l,m}^{\kappa}(t)$ we form the functions $\psi_m(t, \mathbf{x}) := \sum_{l=1}^m a_{l,m}(t) \psi_l(\mathbf{x})$,
15 $\rho_m(t, \mathbf{x}) := \sum_{l=1}^m c_{l,m}(t) \omega_l(\mathbf{x})$, $\xi_m(t, \mathbf{x}) := \sum_{l=1}^m b_{i,l,m}(t) \omega_l(\mathbf{x})$, $\mu_m(t, \mathbf{x}) := \sum_{l=1}^m b_{e,l,m}(t) \mu_l(\mathbf{x})$,
16 and $\omega_m^{\kappa}(t, \mathbf{x}) := \sum_{l=1}^m d_{l,m}^{\kappa}(t) \omega_l(\mathbf{x})$ for $\kappa := w, z, \gamma$. It follows that the Faedo-Galerkin solutions
17 satisfy the following weak formulations for each fixed t , which will be the starting point for deriving
18 a series of a priori estimates:

$$\begin{aligned}
&\varepsilon \int_{\Omega} \partial_t \mathbf{u}_{\varepsilon,m} \cdot \psi_m + \int_{\Omega} \left((\nabla \mathbf{u}_{\varepsilon,m}) \boldsymbol{\sigma}(\mathbf{x}, \gamma_{\varepsilon,m}) : \nabla \psi_m - p_{\varepsilon,m} \nabla \cdot \psi_m \right) d\mathbf{x} \\
&\quad + \int_{\partial\Omega} \alpha \mathbf{u}_{\varepsilon,m} \cdot \psi_m ds = \int_{\Omega} \mathbf{f} \cdot \psi_m d\mathbf{x}, \\
&\varepsilon \int_{\Omega} \partial_t p_{\varepsilon,m} \rho_m + \int_{\Omega} \rho_m \nabla \cdot \mathbf{u}_{\varepsilon,m} = 0, \\
&\int_{\Omega} \partial_t v_{\varepsilon,m} \xi_m + \varepsilon \int_{\Omega} \partial_t v_{i,\varepsilon,m} \xi_m + \int_{\Omega} \left(\mathbf{M}_i(\mathbf{x}, \nabla \mathbf{u}_{\varepsilon,m}) \nabla v_{i,\varepsilon,m} \cdot \nabla \xi_m \right. \\
&\quad \left. + I_{\text{ion}}(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m}) \xi_m \right) d\mathbf{x} = \int_{\Omega} I_s^i \xi_m d\mathbf{x}, \\
&\int_{\Omega} \partial_t v_{\varepsilon,m} \mu_m - \varepsilon \int_{\Omega} \partial_t v_{e,\varepsilon,m} \mu_m - \int_{\Omega} \left(\mathbf{M}_e(\mathbf{x}, \nabla \mathbf{u}_{\varepsilon,m}) \nabla v_{e,\varepsilon,m} \cdot \nabla \mu_m \right. \\
&\quad \left. + I_{\text{ion}}(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m}) \mu_m \right) d\mathbf{x} = \int_{\Omega} I_s^e \mu_m d\mathbf{x}, \\
&\int_{\Omega} \partial_t w_{j,\varepsilon,m} \omega_m^w = \int_{\Omega} R_j(v_{\varepsilon,m}, w_{j,\varepsilon,m}) \omega_m^w, \\
&\int_{\Omega} \partial_t z_{\varepsilon,m} \omega_m^z = \int_{\Omega} G(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m}) \omega_m^z, \\
&\int_{\Omega} \partial_t \gamma_{\varepsilon,m} \omega_m^\gamma = \int_{\Omega} S(\gamma_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}) \omega_m^\gamma,
\end{aligned} \tag{3.6}$$

1 for $j = 1, \dots, k$. To simplify the notation, we perform the derivations in the following three
 2 Lemmata while omitting the subscript ε, m . We start first by obtaining estimates on the gating
 3 and concentration variables ($\mathbf{w}_{\varepsilon, m}$ and $z_{\varepsilon, m}$) that are needed to prove the uniform bounds. In the
 4 following Lemma, we show that the gating variables w_j , $j = 1, \dots, k$ satisfy the universal bounds
 5 $0 \leq w_j \leq 1$.

6 **Lemma 3.1.** *Let $w_j \in C([0, T], L^2(\Omega))$ and $v \in H^1(0, T, L^2(\Omega))$ such that for all $\omega_m^w \in H^1(\Omega)$:*

$$\int_{\Omega} \partial_t w_j \omega_m^w = \int_{\Omega} R_j(v, w_j) \omega_m^w, \quad (3.7)$$

7 where $R_j(v, w_j)$ satisfies assumption (A.6). Assume that $0 \leq w_{j,0} \leq 1$ for a.e. in Ω , then

$$0 \leq w_j \leq 1, \quad \text{a.e. in } \Omega_T. \quad (3.8)$$

8 *Proof.* We first extend the function $R_j(v, w_j)$ by continuity (for $j = 1, \dots, k$):

$$R_j(v, w_j) = \begin{cases} -\beta_j w_j & \text{if } w_j > 1, \\ \alpha_j(1 - w_j) - \beta_j w_j & \text{if } w_j \leq 1 \end{cases} \quad (3.9)$$

We Substitute $\omega_m^w = -w_j^-$ in (3.7) and we use (3.9) to deduce

$$\frac{d}{dt} |w_j^-|^2 \leq 0, \quad \text{for } j = 1, \dots, k.$$

9 Using Gronwall's inequality, we get $w_j^- = 0$ and $w_j \geq 0$, for $j = 1, \dots, k$. Similarly, substituting
 10 $\omega_m^w = (w_j - 1)^+$ in (3.7) and using (3.9), we obtain by using Gronwall's inequality that $w_j \leq 1$,
 11 for a.e. $(t, \mathbf{x}) \in \Omega_T$ and for $j = 1, \dots, k$. \square

12 Now we establish some estimates on the concentration variable z that will help us in getting
 13 the uniform bound on $v_{\varepsilon, m}$. The difficulty arises from the presence of a logarithmic term in the
 14 definition of the function G (2.30) and the ionic current I_{ion} (2.22). So we need to bound z far
 15 from zero. We show in the following Lemma that if the concentration variable z is strictly positive
 16 at the initial time $t = 0$, then it is strictly positive on the interval $[0, T]$ and it cannot approach 0.
 17

18 **Lemma 3.2.** *Let $z \in C([0, T], L^2(\Omega))$, $v \in H^1(0, T, L^2(\Omega))$ and $\mathbf{w} \in C([0, T], L^2(\Omega)^k)$ such that:*

$$\partial_t z = G(v, \mathbf{w}, z), \quad (3.10)$$

where $G(v, \mathbf{w}, z)$ satisfies assumption (A.6) above. Let $z_0 : \Omega \rightarrow (0, +\infty)$ such that:

$$z_0 \in L^2(\Omega), \quad z_0 > 0, \quad \text{for a.e. in } \Omega.$$

19 Then for a.e. $(t, \mathbf{x}) \in [0, T] \times \Omega$, $z > 0$.

20 *Proof.* For a.e. $\mathbf{x} \in \Omega$ fixed, we have $z(0, \mathbf{x}) = z_0 > 0$ and the map: $t \mapsto z(t, \mathbf{x})$ is in $C[0, T]$.
 21 Assume that at some time t , $z(t, \mathbf{x}) = 0$ and let $t_1 = \inf\{t \in (0, T) : z(t, \mathbf{x}) = 0\}$. Using (2.24) and
 22 (2.30), we see that $G(v, \mathbf{w}, z) \rightarrow +\infty$ as $t \rightarrow t_1$. So, for a given $A > 0$ there exists $\delta > 0$ such that
 23 $G(v, \mathbf{w}, z) > A$ for all $t_1 - \delta < t < t_1$. Then using equation (3.10), one obtains $\partial_t z > 0$. Hence, z is
 24 strictly increasing over $[t_1 - \delta, t_1]$. Therefore $z(t_1, \mathbf{x}) > z(t_1 - \delta, \mathbf{x}) > 0$ which is a contradiction.
 25 Consequently by diagonalisation and compactness of $[0, T]$, $z > 0$. \square

26 **Lemma 3.3.** *Under the same assumptions as Lemma 3.2, the concentration variable z satisfies*
 27 *the following estimates for a.e. $\mathbf{x} \in \Omega$, $t \in (0, T)$:*

$$|z(t, \mathbf{x})| \leq C(1 + |z_0(\mathbf{x})| + \|v(\mathbf{x})\|_{L^2(0,t)}), \quad \forall t \in [0, T], \quad (3.11)$$

$$|\ln z(t, \mathbf{x})| \leq C(1 + |z_0(\mathbf{x})| + |v(t, \mathbf{x})| + \|v(\mathbf{x})\|_{L^2(0,t)}) \quad (3.12)$$

$$\int_0^t |\partial_s z|^2 \leq C \left(1 + |z_0 \ln z_0| + |z_0|^2 + \|v\|_{L^2(0,t)}^2 \right), \quad (3.13)$$

$$\int_0^t |\ln z|^2 \leq C \left(1 + |z_0 \ln z_0| + |z_0|^2 + \|v\|_{L^2(0,t)}^2 \right), \quad (3.14)$$

Proof. In our proof, we follow the idea in [6].

Proof of (3.11):

Fixing $\mathbf{x} \in \Omega$ and multiplying equation (3.10) by z , we get

$$z\partial_t z = a_1(a_2 - z)z - a_3 z I_{\text{ion}}^z(v, \mathbf{w}, z, \ln z).$$

Next, we use (2.25) to obtain

$$\frac{1}{2} \frac{d}{dt} |z(t, \cdot)|^2 \leq a_1(a_2 + |z|)|z| - c_1 \sum_{j=1}^k w_j(z \ln z) - c_1 \sum_{j=1}^k z(|v| + w_j),$$

for some constant $c_1 > 0$. Since $-z \ln z \leq \frac{1}{e}$ for all $z \geq 0$ and $0 \leq w_j \leq 1$ a.e. in Ω_T , we find

$$\frac{1}{2} \frac{d}{dt} |z(t, \cdot)|^2 \leq a_1(a_2 + |z|)|z| + \frac{kc_1}{e} + kc_1|z||v|.$$

By Young's inequality, we have

$$\frac{1}{2} \frac{d}{dt} |z(t, \cdot)|^2 \leq \frac{kc_1}{e} + a_1(a_2^2 + \frac{3}{2}|z(t, \cdot)|^2) + \frac{kc_1}{2}|z(t, \cdot)|^2 + \frac{kc_1}{2}|v(t, \cdot)|^2,$$

which can be rewritten as

$$\frac{d}{dt} |z(t, \cdot)|^2 \leq (3a_1 + kc_1)|z(t, \cdot)|^2 + \frac{2kc_1}{e} + 2a_1a_2^2 + kc_1|v(t, \cdot)|^2.$$

By the differential form of Gronwall's inequality, we obtain:

$$|z(t, \cdot)|^2 \leq \exp^{(kc_1 + 3a_1)t} \left[|z_0(\cdot)|^2 + \int_0^t \frac{2kc_1}{e} + 2a_1a_2^2 + kc_1|v(s, \cdot)|^2 ds \right] \quad \forall t \in [0, T].$$

Or equivalently, for positive constants c_2, c_3 and c_4 ,

$$|z(t, \cdot)|^2 \leq e^{c_2 t} \left[|z_0(\cdot)|^2 + c_3 t + c_4 \int_0^t |v(s, \cdot)|^2 ds \right] \quad \forall t \in [0, T].$$

We conclude that there exists a constant $c_5 > 0$, dependent on T such that

$$|z(t, \cdot)| \leq c_5(1 + |z_0(\cdot)| + \|v(\cdot)\|_{L^2(0,t)}) \quad \forall t \in [0, T]$$

Proof of (3.12):

In order to prove this estimate, we fix $\mathbf{x} \in \Omega$ and we use definition (2.30) of the function G in equation (3.10) to get

$$\frac{dz}{dt} = a_1(a_2 - z) - a_3 I_{\text{ion}}^z(v, \mathbf{w}, z, \ln z).$$

Exploiting (2.24) and the uniform boundedness of \mathbf{w} in Lemma 3.1, we get

$$\frac{dz}{dt} \geq c_6 - c_7|z| - c_8(|v| + \ln z),$$

- 1 for some positive constants $c_6, c_7, c_8 > 0$. By (3.11), we have

$$\frac{dz}{dt} \geq c_6 - c_9(1 + |z_0(\cdot)| + \|v\|_{L^2(0,t)}) - c_8|v| - c_8 \ln z, \quad (3.15)$$

- 2 for some constant $c_9 > 0$. After rearrangement of the inequality, we obtain:

$$c_8 \ln z \geq c_6 - c_9(1 + |z_0(\cdot)| + \|v\|_{L^2(0,t)}) - c_8|v| - \frac{dz}{dt}. \quad (3.16)$$

- 3 Furthermore, since $\frac{dz}{dt}$ is continuous over $[0, T]$, it is bounded below and there exists a constant
4 c_{10} such that:

$$\ln z \geq c_{10}(1 + |z_0(\cdot)| + |v(t, \cdot)| + \|v\|_{L^2(0,t)}) \quad (3.17)$$

- 5 On the other hand, knowing that $\ln z < z$, one has by (3.11):

$$\ln z < C(1 + |z_0(\cdot)| + \|v\|_{L^2(0,t)}) \leq C(1 + |z_0(\cdot)| + |v(t, \cdot)| + \|v\|_{L^2(0,t)}). \quad (3.18)$$

Estimate (3.12) follows easily from (3.17) and (3.18).

Proof of (3.13):

We fix $\mathbf{x} \in \Omega$, we multiply equation (3.10) by $\frac{dz}{dt}$ and we use (2.30) to get

$$\left(\frac{dz}{dt}\right)^2 = a_1(a_2 - z)\frac{dz}{dt} - a_3 \ln z \frac{dz}{dt} \left[\frac{I_{\text{ion}}^z(v, \mathbf{w}, z, \ln z) - I_{\text{ion}}^z(v, \mathbf{w}, z, 0)}{\ln z} \right] - a_3 I_{\text{ion}}^z(v, \mathbf{w}, z, 0) \frac{dz}{dt}.$$

Letting

$$\Theta(t) = \frac{I_{\text{ion}}^z(v, \mathbf{w}, z, \ln z) - I_{\text{ion}}^z(v, \mathbf{w}, z, 0)}{\ln z}$$

and observing that

$$\frac{dz}{dt} \ln z = \frac{d}{dt} [z \ln z - z].$$

The above equation simplifies to

$$\left(\frac{dz}{dt}\right)^2 = \left[a_1(a_2 - z) - a_3 I_{\text{ion}}^z(v, \mathbf{w}, z, 0) \right] \frac{dz}{dt} - a_3 \Theta(t) \frac{d}{dt} (z \ln z - z).$$

Therefore

$$\int_0^t \frac{1}{\Theta(s)} \left(\frac{dz}{ds}\right)^2 ds = \int_0^t \left[\frac{a_1(a_2 - z) - a_3 I_{\text{ion}}^z(v, \mathbf{w}, z, 0)}{\Theta(s)} \right] \frac{dz}{ds} ds - a_3 (z \ln z - z - z_0 \ln z_0 + z_0).$$

- 1 Note that by (2.26), the mean value theorem and Lemma 3.1, there exist $\theta_1, \theta_2 > 0$ such that

$$\theta_2 \leq \Theta(t) \leq \theta_1. \quad (3.19)$$

Using $z \ln z - z \geq -1$, (3.19) and (2.24), we get:

$$\int_0^t \frac{1}{\Theta(s)} \left(\frac{dz}{ds}\right)^2 ds \leq \frac{1}{\theta_2} \int_0^t \left(a_1 a_2 + a_1 |z| + a_3 C(1 + |v| + |z|) \right) \left| \frac{dz}{ds} \right| ds + a_3 (1 + z_0 \ln z_0 - z_0).$$

By (3.19), there holds

$$\frac{1}{\theta_1} \int_0^t \left(\frac{dz}{ds}\right)^2 ds \leq \frac{1}{\theta_2} \int_0^t \left(a_1 a_2 + a_1 |z| + a_3 C(1 + |v| + |z|) \right) \left| \frac{dz}{ds} \right| ds + a_3 (1 + z_0 \ln z_0 - z_0).$$

Now, by estimate (3.11) with C denoted by C' , one gets

$$\begin{aligned} \frac{1}{\theta_1} \int_0^t \left(\frac{dz}{ds}\right)^2 ds &\leq \frac{1}{\theta_2} \int_0^t \left(a_1 a_2 + a_3 C + (a_1 + a_3 C) C'(1 + |z_0| + \|v(\mathbf{x})\|_{L^2(0,s)}) \right. \\ &\quad \left. + a_3 C |v| \right) \left| \frac{dz}{ds} \right| ds + a_3 (1 + z_0 \ln z_0 - z_0). \end{aligned}$$

Applying Cauchy's inequality with $\varepsilon = \frac{1}{2} \frac{\theta_2}{\theta_1}$ on the integrand of the right hand side of this last inequality, we obtain:

$$\begin{aligned} \frac{1}{\theta_1} \int_0^t \left(\frac{dz}{ds}\right)^2 ds &\leq \frac{\theta_1}{2(\theta_2)^2} \int_0^t \left(a_1 a_2 + a_3 C + (a_1 + a_3 C) C'(1 + |z_0| + \|v(\mathbf{x})\|_{L^2(0,s)}) \right. \\ &\quad \left. + a_3 C |v| \right)^2 ds + \frac{1}{2\theta_1} \int_0^t \left| \frac{dz}{ds} \right|^2 ds + a_3 (1 + z_0 \ln z_0 - z_0). \end{aligned}$$

Consequently,

$$\begin{aligned} \frac{1}{2\theta_1} \int_0^t \left(\frac{dz}{ds}\right)^2 ds &\leq \frac{\theta_1}{2(\theta_2)^2} \int_0^t \left(a_1 a_2 + a_3 C + (a_1 + a_3 C) C'(1 + |z_0| + \|v(\mathbf{x})\|_{L^2(0,s)}) \right. \\ &\quad \left. + a_3 C |v| \right)^2 ds + a_3 (1 + z_0 \ln z_0 - z_0). \end{aligned}$$

- 2 Finally, one can easily show that there exists $c_{11} > 0$ depending on T such that

$$\int_0^t \left(\frac{dz}{ds}\right)^2 ds \leq c_{11} \left(1 + |z_0 \ln z_0 - z_0| + |z_0|^2 + \|v(\mathbf{x})\|_{L^2(0,t)}^2 \right), \quad \forall t \in (0, T), \quad (3.20)$$

- 3 for some constant $c_{11} > 0$.

Proof of (3.14):

We have by (2.16) and (2.30)

$$I_{\text{ion}}^z(v, \mathbf{w}, z, \ln z) = \frac{1}{a_3} \left[a_1(a_2 - z) - \frac{dz}{dt} \right].$$

We rewrite it as:

$$\left(\frac{I_{\text{ion}}^z(v, \mathbf{w}, z, \ln z) - I_{\text{ion}}^z(v, \mathbf{w}, z, 0)}{\ln z} \right) \ln z = \frac{1}{a_3} \left[a_1(a_2 - z) - \frac{dz}{dt} \right] - I_{\text{ion}}^z(v, \mathbf{w}, z, 0).$$

After squaring both sides, we obtain:

$$\underline{\Theta}^2 (\ln z)^2 \leq 3 \left(\frac{a_1^2 (a_2 - z)^2}{a_3^2} + \frac{1}{a_3^2} \left(\frac{dz}{dt} \right)^2 + I_{\text{ion}}^z(v, \mathbf{w}, z, 0)^2 \right).$$

Then we integrate over $(0, t)$, to get:

$$\int_0^t \underline{\Theta}^2 (\ln z)^2 ds \leq 3 \int_0^t \left(\frac{a_1^2 (a_2 - z)^2}{a_3^2} + \frac{1}{a_3^2} \left(\frac{dz}{dt} \right)^2 + I_{\text{ion}}^z(v, \mathbf{w}, z, 0)^2 \right) ds.$$

Therefore, by (3.11), (3.20) and (2.24) we find

$$\int_0^t (\ln z(s))^2 ds \leq c_{12} \left(1 + |z_0 \ln z_0 - z_0| + |z_0|^2 + \|v\|_{L^2(0,t)}^2 \right),$$

1 for some constant $c_{12} > 0$. □

2 Using the above estimates on z and \mathbf{w} , we shall control the L^2 norm of I_{ion} by the L^2 norm of
3 v and this result will be later used to reach a uniform in ε and m estimate on $v_{\varepsilon, m}$.

4 **Lemma 3.4.** *Under the same conditions of Lemma 3.3, there exists a constant $C > 0$ (dependent*
5 *on T) such that*

$$\|I_{\text{ion}}(v, \mathbf{w}, z, \ln(z))\|_{L^2(\Omega_T)}^2 \leq C(1 + \|v\|_{L^2(\Omega_T)}^2). \quad (3.21)$$

Proof. By definition (2.22) of I_{ion} , by properties (2.23) and (2.24), and **by the uniform bound obtained on w_j (3.8), there holds:**

$$|I_{\text{ion}}(v, \mathbf{w}, z, \ln(z))|^2 \leq C \left(\sum_{j=1}^k (1 + |v|^2) + 1 + |v|^2 + |z|^2 + |\ln z|^2 \right) \quad (C \text{ is a generic constant}).$$

6 Using (3.11) and (3.12), one obtains

$$|I_{\text{ion}}(v, \mathbf{w}, z, \ln(z))|^2 \leq C(1 + |z_0|^2 + |v|^2 + \|v\|_{L^2(0,t)}^2) \quad (3.22)$$

7 Finally, integrate (3.22) over $(0, t) \times \Omega$ and use (3.14) along with the condition that z_0 is in $L^2(\Omega)$,
8 to get (3.21). □

9 We recall that in order to establish the passage to the limit as $m \rightarrow \infty$, we need to bound the
10 solutions of the discrete regularized problem in various Banach spaces, making use of the preceding
11 estimates.

12 **Lemma 3.5.** *There exist constants $\mathcal{C}_1, \mathcal{C}_2$ and $\mathcal{C}_3 > 0$ independent of ε and m such that*

$$\max_{t \in [0, T]} \left(\|v_{\varepsilon, m}(t)\|_{L^2(\Omega)} + \sum_{j=i, e} \|\sqrt{\varepsilon} v_{j, \varepsilon, m}(t)\|_{L^2(\Omega)} \right) \leq \mathcal{C}_1, \quad (3.23)$$

$$\left(\sum_{j=i, e} \|v_{j, \varepsilon, m}\|_{L^2(0, T; H^1(\Omega))} + \|v_{\varepsilon, m}\|_{L^2(0, T; H^1(\Omega))} \right) \leq \mathcal{C}_2, \quad (3.24)$$

$$\|\partial_t(v_{\varepsilon, m} + \varepsilon v_{i, \varepsilon, m})\|_{L^2(0, T; (H^1(\Omega))')} + \|\partial_t(v_{\varepsilon, m} - \varepsilon v_{e, \varepsilon, m})\|_{L^2(0, T; (H^1(\Omega))')} \leq \mathcal{C}_3, \quad (3.25)$$

1 *Proof.*

2 *Proofs of (3.23) and (3.24):*

3 First, we make use of the relation $v_{\varepsilon,m} = v_{i,\varepsilon,m} - v_{e,\varepsilon,m}$. We take $\xi_m := v_{i,\varepsilon,m}$ and $\mu_m := -v_{e,\varepsilon,m}$
 4 as test functions in (3.6) to get

$$\begin{aligned} \int_{\Omega} v_{i,\varepsilon,m} \partial_t v_{\varepsilon,m} + \varepsilon \int_{\Omega} v_{i,\varepsilon,m} \partial_t v_{i,\varepsilon,m} + \int_{\Omega} \left(\mathbf{M}_i(\mathbf{x}, \nabla \mathbf{u}_{\varepsilon,m}) \nabla v_{i,\varepsilon,m} \cdot \nabla v_{i,\varepsilon,m} \right. \\ \left. + I_{\text{ion}}(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m}) v_{i,\varepsilon,m} \right) d\mathbf{x} = \int_{\Omega} I_s^i v_{i,\varepsilon,m} d\mathbf{x}, \end{aligned} \quad (3.26)$$

$$\begin{aligned} - \int_{\Omega} v_{e,\varepsilon,m} \partial_t v_{\varepsilon,m} + \varepsilon \int_{\Omega} v_{e,\varepsilon,m} \partial_t v_{e,\varepsilon,m} + \int_{\Omega} \left(\mathbf{M}_e(\mathbf{x}, \nabla \mathbf{u}_{\varepsilon,m}) \nabla v_{e,\varepsilon,m} \cdot \nabla v_{e,\varepsilon,m} \right. \\ \left. - I_{\text{ion}}(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m}) v_{e,\varepsilon,m} \right) d\mathbf{x} = - \int_{\Omega} I_s^e v_{e,\varepsilon,m} d\mathbf{x}. \end{aligned} \quad (3.27)$$

5 Secondly, we add equations (3.26) and (3.27) to obtain

$$\begin{aligned} \int_{\Omega} \left(I_{\text{ion}}(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m}) v_{\varepsilon,m} + \sum_{j=i,e} \mathbf{M}_j(\mathbf{x}, \nabla \mathbf{u}_{\varepsilon,m}) \nabla v_{j,\varepsilon,m} \cdot \nabla v_{j,\varepsilon,m} \right) \\ + \frac{1}{2} \int_{\Omega} |\partial_t v_{\varepsilon,m}|^2 + \frac{1}{2} \sum_{k=i,e} \int_{\Omega} |\sqrt{\varepsilon} \partial_t v_{k,\varepsilon,m}|^2 = \int_{\Omega} (I_s^i v_{i,\varepsilon,m} - I_s^e v_{e,\varepsilon,m}). \end{aligned} \quad (3.28)$$

6 Then we integrate equation (3.28) on $(0, s)$ for every $s \leq T$, to get:

$$\begin{aligned} \int_0^s \int_{\Omega} \left(I_{\text{ion}}(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m}) v_{\varepsilon,m} + \sum_{j=i,e} \mathbf{M}_j(\mathbf{x}, \nabla \mathbf{u}_{\varepsilon,m}) \nabla v_{j,\varepsilon,m} \cdot \nabla v_{j,\varepsilon,m} \right) \\ + \frac{1}{2} \int_{\Omega} |v_{\varepsilon,m}(s, \cdot)|^2 + \frac{1}{2} \sum_{k=i,e} \int_{\Omega} |\sqrt{\varepsilon} v_{k,\varepsilon,m}(s, \cdot)|^2 \\ = \frac{1}{2} \int_{\Omega} |v_{0,\varepsilon,m}|^2 + \frac{1}{2} \sum_{k=i,e} \int_{\Omega} |\sqrt{\varepsilon} v_{k,0,\varepsilon,m}|^2 + \int_0^s \int_{\Omega} (I_s^i v_{i,\varepsilon,m} - I_s^e v_{e,\varepsilon,m}) \\ = \frac{1}{2} \int_{\Omega} |v_{0,\varepsilon,m}|^2 + \frac{1}{2} \sum_{k=i,e} \int_{\Omega} |\sqrt{\varepsilon} v_{k,0,\varepsilon,m}|^2 + \int_0^s \int_{\Omega} \left(I_s^i v_{\varepsilon,m} + (I_s^i - I_s^e) v_{e,\varepsilon,m} \right). \end{aligned} \quad (3.29)$$

Note that, by construction, $|v_{j,0,\varepsilon,m}| \leq \frac{|v_{0,\varepsilon,m}|}{2} + \frac{1}{|\Omega|} \left| \int_{\Omega} \frac{v_{0,\varepsilon,m}}{2} \right|$, $j = i, e$. Using this, the ellipticity condition **(A.3)**, Young's and Hölder's inequalities, and in addition estimate (3.21) on I_{ion} in Lemma 3.4 and Poincaré's inequality with compatibility condition (2.31), we get

$$\begin{aligned} \frac{1}{c} \sum_{j=i,e} \|\nabla v_{j,\varepsilon,m}\|_{L^2(\Omega_s)}^2 + \frac{1}{2} \|v_{\varepsilon,m}(s)\|_{L^2(\Omega)}^2 + \frac{1}{2} \sum_{j=i,e} \|\sqrt{\varepsilon} v_{j,\varepsilon,m}\|_{L^2(\Omega)}^2 \\ \leq \left(\varepsilon + \frac{1}{2} \right) \|v_{0,\varepsilon,m}\|_{L^2(\Omega)}^2 + \|I_i^s\|_{L^2(\Omega_s)} \|v_{\varepsilon,m}\|_{L^2(\Omega_s)} + \sum_{j=i,e} \|I_j^s\|_{L^2(\Omega_s)} \|v_{e,\varepsilon,m}\|_{L^2(\Omega_s)} \\ + \frac{1}{2} \|I_{\text{ion}}(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m})\|_{L^2(\Omega_s)}^2 + \frac{1}{2} \|v_{\varepsilon,m}\|_{L^2(\Omega_s)}^2 \\ \leq \left(\varepsilon + \frac{1}{2} \right) \|v_{0,\varepsilon,m}\|_{L^2(\Omega)}^2 + \frac{1}{2} \|I_i^s\|^2 + \frac{1}{2} \|v_{\varepsilon,m}\|_{L^2(\Omega_s)}^2 + \frac{c}{2} \sum_{j=i,e} \|I_j^s\|_{L^2(\Omega_s)}^2 + \frac{1}{2c} \|\nabla v_{e,\varepsilon,m}\|_{L^2(\Omega_s)}^2 \\ + \frac{C}{2} \left(1 + \|v_{\varepsilon,m}\|_{L^2(\Omega_s)}^2 \right) + \frac{1}{2} \|v_{\varepsilon,m}\|_{L^2(\Omega_s)}^2 \\ \leq \left(\varepsilon + \frac{1}{2} \right) \|v_0\|_{L^2(\Omega)}^2 + \frac{1}{2} \left((1+c) \|I_i^s\|^2 + \|I_e^s\|^2 \right) + \frac{1}{2c} \|\nabla v_{e,\varepsilon,m}\|_{L^2(\Omega_s)}^2 \\ + \left(\frac{C}{2} + 1 \right) \|v_{\varepsilon,m}\|_{L^2(\Omega_s)}^2 + \frac{C}{2}, \end{aligned}$$

1 where $C > 0$ is the constant of estimate (3.21). Or equivalently:

$$\begin{aligned} \|v_{\varepsilon,m}(s)\|_{L^2(\Omega)}^2 + \sum_{j=i,e} \|\sqrt{\varepsilon}v_{j,\varepsilon,m}(t)\|_{L^2(\Omega)}^2 - c_{13}\|v_{\varepsilon,m}\|_{L^2(\Omega_s)}^2 \\ + \frac{2}{c}\|\nabla v_{i,\varepsilon,m}\|_{L^2(\Omega_s)}^2 + \frac{1}{c}\|\nabla v_{e,\varepsilon,m}\|_{L^2(\Omega_s)}^2 \leq c_{14}, \end{aligned} \quad (3.30)$$

where $c_{13} = \left(C + \frac{1}{2}\right)$ and $c_{14} > 0$ is obtained from the L^2 -norms of $I_{i,e}^s$ and v_0 . This implies

$$\|v_{\varepsilon,m}(s)\|_{L^2(\Omega)}^2 - c_{15} \int_0^s \|v_{\varepsilon,m}(t)\|_{L^2(\Omega)}^2 dt \leq c_{16},$$

for some constants $c_{15}, c_{16} > 0$. **An application of Gronwall's inequality yields**

$$\|v_{\varepsilon,m}(t)\|_{L^2(\Omega)}^2 \leq c_{16}(1 + c_{15}te^{c_{15}t}), \quad \forall t \in (0, T).$$

Hence, one obtains

$$\max_{t \in [0, T]} \|v_{\varepsilon,m}(t)\|_{L^2(\Omega)}^2 \leq c_{17},$$

2 for some constant $c_{17} > 0$. Using this and (3.30), (3.23) is proved. Again using (3.30), we have
3 for all $t \in (0, T)$

$$c_{18} \sum_{j=i,e} \|\nabla v_{j,\varepsilon,m}\|_{L^2(\Omega)}^2 + \|v_{\varepsilon,m}(t)\|_{L^2(\Omega)}^2 \leq c_{14} + c_{13}\|v_{\varepsilon,m}\|_{L^2(\Omega_t)}^2 := c_{19}, \quad (3.31)$$

4 for some constants $c_{18}, c_{19} > 0$. **The last inequality implies the bound on $v_{i,\varepsilon,m}$, $v_{e,\varepsilon,m}$ and $v_{\varepsilon,m}$**
5 **in $L^2(0, T; H^1(\Omega))$** (recall that $v_{\varepsilon,m} = v_{i,\varepsilon,m} - v_{e,\varepsilon,m}$). The proof of estimate (3.24) is thus achieved.

6

Proof of (3.25):

In order to prove (3.25), we introduce the sequences $U_{i,\varepsilon,m} = v_{\varepsilon,m} + \varepsilon v_{i,\varepsilon,m}$ and $U_{e,\varepsilon,m} = v_{\varepsilon,m} - \varepsilon v_{e,\varepsilon,m}$. Indeed, $\partial_t U_{i,\varepsilon,m}$ and $\partial_t U_{e,\varepsilon,m}$ are bounded (independent of ε) in $L^2(0, T; (H^1(\Omega))')$; this is easily seen by the following argument:

We let $\varphi \in L^2(0, T; H^1(\Omega))$, we take $\xi_m := \varphi$ in (3.6) and we exploit assumption **(A.3)** to get from (3.23) and (3.24)

$$\begin{aligned} \int_0^T |\langle \partial_t U_{i,\varepsilon,m}, \varphi \rangle_{(H^1)', H^1}| dt &= \int_0^T |(\partial_t U_{i,\varepsilon,m}, \varphi)_{L^2}| dt \\ &= \int_0^T |-(\mathbf{M}_i(\mathbf{x}, \nabla \mathbf{u}_{\varepsilon,m}) \nabla v_{i,\varepsilon,m}, \nabla \varphi)_{L^2} + (-I_{\text{ion}} + I_s^i, \varphi)_{L^2}| dt \\ &\leq \int_0^T \left(\|\mathbf{M}_i(\cdot, \nabla \mathbf{u}_{\varepsilon,m}) \nabla v_{i,\varepsilon,m}\|_{L^2} \|\nabla \varphi\|_{L^2} + \| -I_{\text{ion}} + I_s^i \|_{L^2} \|\varphi\|_{L^2} \right) dt \\ &\leq c_{20} \left(\|\nabla v_{i,\varepsilon,m}\|_{L^2(\Omega_T)} + \|I_{\text{ion}}\|_{L^2(\Omega_T)} + \|I_s^i\|_{L^2(\Omega_T)} \right) \|\varphi\|_{L^2(0, T; H^1(\Omega))} \\ &\leq c_{21} \|\varphi\|_{L^2(0, T; H^1(\Omega))}, \end{aligned}$$

7 for some constants $c_{20}, c_{21} > 0$. This implies that $\partial_t U_{i,\varepsilon,m}$ is uniformly bounded in $L^2(0, T; (H^1(\Omega))')$.
8 The bound of $\partial_t U_{e,\varepsilon,m}$ in $L^2(0, T; (H^1(\Omega))')$ follows by a similar argument.

9

10 □

11 Regarding the gating, the activation and the concentration variables, we have the following
12 result.

13 **Lemma 3.6.** *There exist constants \mathcal{C}_4 and $\mathcal{C}_5 > 0$ independent of ε and m such that:*

$$\|\mathbf{w}_{\varepsilon,m}\|_{L^2(0, T; H^1(\Omega)^k)} + \|z_{\varepsilon,m}\|_{L^2(0, T; H^1(\Omega))} + \|\gamma_{\varepsilon,m}\|_{L^2(0, T; H^1(\Omega))} \leq \mathcal{C}_4, \quad (3.32)$$

$$\|\partial_t \mathbf{w}_{\varepsilon,m}\|_{L^2(\Omega_T)^k} + \|\partial_t z_{\varepsilon,m}\|_{L^2(\Omega_T)} + \|\partial_t \gamma_{\varepsilon,m}\|_{L^2(\Omega_T)} \leq \mathcal{C}_5. \quad (3.33)$$

Proof.

Proof of (3.32):

We turn now to the gating variables $w_{j,\varepsilon,m}$ (recall that $0 \leq w_{j,\varepsilon,m} \leq 1$). Observe that by differentiation of equation (2.15) with respect to \mathbf{x} and by the chain rule, one has

$$\partial_t \nabla w_{j,\varepsilon,m} = \frac{d\alpha_j}{dv} \nabla v_{\varepsilon,m} (1 - w_{j,\varepsilon,m}) - (\alpha_j + \beta_j) \nabla w_{j,\varepsilon,m} - \frac{d\beta_j}{dv} \nabla v_{\varepsilon,m} w_{j,\varepsilon,m}.$$

- 1 Multiplying this equation by $\nabla w_{j,\varepsilon,m}$ and using the assumption (A.6) (recall that $\frac{d\alpha_j}{dv}$ and $\frac{d\beta_j}{dv}$
- 2 are uniformly bounded in L^∞), we get

$$\begin{aligned} \frac{1}{2} \partial_t |\nabla w_{j,\varepsilon,m}|^2 &\leq \left| \frac{d\alpha_j}{dv} \nabla v_{\varepsilon,m} \nabla w_{j,\varepsilon,m} \right| + \left| \frac{d\beta_j}{dv} \nabla v_{\varepsilon,m} \nabla w_{j,\varepsilon,m} \right| \\ &\leq \frac{\left| \frac{d\alpha_j}{dv} \nabla v_{\varepsilon,m} \right|^2}{2} + \frac{|\nabla w_{j,\varepsilon,m}|^2}{2} + \frac{\left| \frac{d\beta_j}{dv} (v_{\varepsilon,m}) \nabla v_{\varepsilon,m} \right|^2}{2} + \frac{|\nabla w_{j,\varepsilon,m}|^2}{2} \\ &\leq c_{22} (|\nabla v_{\varepsilon,m}|^2 + |\nabla w_{j,\varepsilon,m}|^2), \end{aligned}$$

for some positive constant c_{22} . An application of Gronwall's inequality and (3.24) yield

$$\|\nabla w_{j,\varepsilon,m}(t)\|_{L^2(\Omega)} \leq \mathcal{C}(T, \Omega, \|\nabla w_{j,0}\|_{L^2(\Omega)}),$$

for all $t \in (0, T)$. Estimate (3.32) for $w_{j,\varepsilon,m}$ follows easily. Now to obtain the uniform bound on the concentration variable $z_{\varepsilon,m}$, we integrate (3.11) to get

$$\int_{\Omega} |z_{\varepsilon,m}(x, t)|^2 \leq c_{23} \left(1 + \|z_0\|_{L^2(\Omega)}^2 + \|v_{\varepsilon,m}\|_{L^2(\Omega_T)}^2 \right), \quad \forall t \in [0, T].$$

Using (3.23) for $v_{\varepsilon,m}$, this implies the uniform bound of $z_{\varepsilon,m}$ in $L^\infty(0, T; L^2(\Omega))$. Now we differentiate both sides of equation (2.16) with respect to \mathbf{x} and then use (2.30) to obtain

$$\partial_t \nabla z_{\varepsilon,m} = -a_1 \nabla z_{\varepsilon,m} - a_3 \left(\frac{\partial I_{\text{ion}}^z}{\partial v} \nabla v_{\varepsilon,m} + \sum_{j=1}^k \frac{\partial I_{\text{ion}}^z}{\partial w_j} \nabla w_{j,\varepsilon,m} + \frac{\partial I_{\text{ion}}^z}{\partial z} \nabla z_{\varepsilon,m} + \frac{\partial I_{\text{ion}}^z}{\partial \zeta} \frac{1}{z_{\varepsilon,m}} \nabla z_{\varepsilon,m} \right).$$

Multiplying this equation by $\nabla z_{\varepsilon,m}$, using (2.26) and (2.29), we get

$$\begin{aligned} \frac{1}{2} \partial_t |\nabla z_{\varepsilon,m}|^2 &= -a_1 |\nabla z_{\varepsilon,m}|^2 - a_3 \left(\frac{\partial I_{\text{ion}}^z}{\partial v} \nabla v_{\varepsilon,m} \cdot \nabla z_{\varepsilon,m} + \sum_{j=1}^k \frac{\partial I_{\text{ion}}^z}{\partial w_j} \nabla w_{j,\varepsilon,m} \cdot \nabla z_{\varepsilon,m} \right. \\ &\quad \left. + \frac{\partial I_{\text{ion}}^z}{\partial z} |\nabla z_{\varepsilon,m}|^2 + \frac{\partial I_{\text{ion}}^z}{\partial \zeta} \frac{1}{z_{\varepsilon,m}} |\nabla z_{\varepsilon,m}|^2 \right) \\ &\leq -a_3 \left(\frac{\partial I_{\text{ion}}^z}{\partial v} \nabla v_{\varepsilon,m} \cdot \nabla z_{\varepsilon,m} + \sum_{j=1}^k \frac{\partial I_{\text{ion}}^z}{\partial w_j} \nabla w_{j,\varepsilon,m} \cdot \nabla z_{\varepsilon,m} \right) \\ &\leq a_3 \left(\left| \frac{\partial I_{\text{ion}}^z}{\partial v} \nabla v_{\varepsilon,m} \cdot \nabla z_{\varepsilon,m} \right| + \sum_{j=1}^k \left| \frac{\partial I_{\text{ion}}^z}{\partial w_j} \nabla w_{j,\varepsilon,m} \cdot \nabla z_{\varepsilon,m} \right| \right) \\ &\leq \frac{a_3}{2} \left| \frac{\partial I_{\text{ion}}^z}{\partial v} \nabla v_{\varepsilon,m} \right|^2 + \frac{a_3}{2} |\nabla z_{\varepsilon,m}|^2 + \frac{a_3}{2} \sum_{j=1}^k \left| \frac{\partial I_{\text{ion}}^z}{\partial w_j} \nabla w_{j,\varepsilon,m} \right|^2 + \frac{ka_3}{2} |\nabla z_{\varepsilon,m}|^2. \end{aligned}$$

By assumptions (2.27) and (2.28), we deduce

$$\partial_t |\nabla z_{\varepsilon,m}|^2 \leq c_{24} \left(1 + |\nabla z_{\varepsilon,m}|^2 + |\nabla v_{\varepsilon,m}|^2 + |v_{\varepsilon,m}|^2 + |\ln z_{\varepsilon,m}|^2 + \sum_{j=1}^k |\nabla w_{j,\varepsilon,m}|^2 \right),$$

for some constant $c_{24} > 0$. Using Gronwall's inequality, we get

$$|\nabla z_{\varepsilon,m}(t)|^2 \leq e^{c_{24}t} \left(|\nabla z_0|^2 + c_{24} \int_0^t (|\nabla v_{\varepsilon,m}|^2 + |v_{\varepsilon,m}|^2 + |\ln z_{\varepsilon,m}|^2 + \sum_{j=1}^k |\nabla w_{j,\varepsilon,m}|^2 + 1) ds \right),$$

1 for all $t \in (0, T)$. Estimate (3.32) for $z_{\varepsilon, m}$ is a consequence of (3.14), (3.24) and the uniform bound
 2 of $w_{j, \varepsilon, m}$ in $L^2(H^1)$ for $j = 1, \dots, k$.

3

Now, we substitute $\omega_m^\gamma := \gamma_{\varepsilon, m}$ into the equation satisfied by γ in (3.6) to deduce after an
 integration in time t and an application of Young's inequality (recall the definition of the function
 S in (A.5))

$$\begin{aligned} & \frac{1}{2} \|\gamma_{\varepsilon, m}(s)\|_{L^2(\Omega)}^2 + \beta \eta_0 \int_0^s \|\gamma_{\varepsilon, m}(t)\|_{L^2(\Omega)}^2 dt \\ &= \frac{1}{2} \|\gamma_{\varepsilon, m}(0)\|_{L^2(\Omega)}^2 + \beta \sum_{j=1}^k \eta_j \int_0^s \int_{\Omega} \gamma_{\varepsilon, m} w_{j, \varepsilon, m} d\mathbf{x} dt \\ &\leq \frac{1}{2} \|\gamma_{\varepsilon, m}(0)\|_{L^2(\Omega)}^2 + \frac{k\beta\eta}{2} \int_0^s \|\gamma_{\varepsilon, m}(t)\|_{L^2(\Omega)}^2 dt + \frac{\beta\eta}{2} \sum_{j=1}^k \int_0^s \|w_{j, \varepsilon, m}(t)\|_{L^2(\Omega)}^2 dt. \end{aligned}$$

for $s \in (0, T)$, where $\eta = \max_{j=1, \dots, k} \eta_j$. This implies

$$\begin{aligned} \|\gamma_{\varepsilon, m}(s)\|_{L^2(\Omega)}^2 &\leq (k\beta\eta - 2\beta\eta_0) \int_0^s \|\gamma_{\varepsilon, m}(t)\|_{L^2(\Omega)}^2 dt + \|\gamma_{\varepsilon, m}(0)\|_{L^2(\Omega)}^2 \\ &\quad + \beta\eta \sum_{j=1}^k \|w_{j, \varepsilon, m}\|_{L^2(\Omega_T)}^2 \\ &\leq c_{25} \int_0^s \|\gamma_{\varepsilon, m}(t)\|_{L^2(\Omega)}^2 dt + \|\gamma(0)\|_{L^2(\Omega)}^2 + \beta\eta k c_{26}, \end{aligned}$$

where $c_{25} = -2\beta\eta_0 + k\beta\eta$ and $c_{26} > 0$. Let $\tilde{C} = \|\gamma(0)\|_{L^2(\Omega)}^2 + \beta\eta k c_{26}$, by Gronwall's lemma, we
 obtain

$$\|\gamma_{\varepsilon, m}(t)\|_{L^2(\Omega)}^2 \leq \tilde{C}(1 + c_{25} t e^{c_{25} t}) < c_{27},$$

for $t \in (0, T)$ and c_{27} a positive constant. This gives the $L^2(\Omega_T)$ uniform bound of $\gamma_{\varepsilon, m}$.
 Now, differentiating (2.17) with respect to \mathbf{x} and multiplying by $\nabla \gamma_{\varepsilon, m}$, we get

$$\begin{aligned} \frac{1}{2} \partial_t |\nabla \gamma_{\varepsilon, m}|^2 &\leq \beta \sum_{j=1}^k \eta_j |\nabla \gamma_{\varepsilon, m} \cdot \nabla w_{j, \varepsilon, m}| + \beta \eta_0 |\nabla \gamma_{\varepsilon, m}|^2 \\ &\leq \left(\frac{\beta k \eta}{2} + \beta \eta_0 \right) |\nabla \gamma_{\varepsilon, m}|^2 + \frac{\beta \eta}{2} |\nabla w_{\varepsilon, m}|^2. \end{aligned}$$

An application of Gronwall's inequality, we deduce

$$|\nabla \gamma_{\varepsilon, m}|^2 \leq e^{(\beta k \eta + 2\beta \eta_0)t} |\nabla \gamma_0|^2 + \beta \eta \int_0^t |\nabla w_{\varepsilon, m}|^2 ds.$$

4 Upon integration of this inequality over Ω_T , we get the uniform bound of $\nabla \gamma_{\varepsilon, m}$ in L^2 . This
 5 concludes the proof of (3.32)

6

Proof of (3.33):

To prove the L^2 uniform bound of $\partial_t w_{j, \varepsilon, m}$ we exploit $0 \leq w_{j, \varepsilon, m} \leq 1$ and $\beta_j(v) > 0$ in the
 following equation

$$\begin{aligned} \partial_t w_{j, \varepsilon, m} &= \alpha_j(v_{\varepsilon, m})(1 - w_{j, \varepsilon, m}) - \beta_j(v_{\varepsilon, m}) w_{j, \varepsilon, m} \\ &\leq \alpha_j(v_{\varepsilon, m}) \\ &\leq C(1 + |v_{\varepsilon, m}|), \end{aligned}$$

where the last inequality follows from (2.21). Squaring both sides, integrating over Ω_T and using
 the uniform estimate on $\|v_{\varepsilon, m}\|_{L^2(\Omega_T)}$, we obtain (for a positive constant c_{28} dependent on T)

$$\|\partial_t w_{j, \varepsilon, m}\|_{L^2(\Omega_T)}^2 \leq c_{28}(T).$$

Now the $L^2(\Omega_T)$ uniform estimate on $\partial_t z_{\varepsilon,m}$ is a direct consequence of the structure of the governing equation along with (2.30), (2.24) and Lemmata 3.1 and 3.3. Actually, squaring both sides of (2.16), and using the inequality $(a-b)^2 \leq 2a^2 + 2b^2$ twice, we have

$$|\partial_t z_{\varepsilon,m}|^2 \leq 4a_1^2(a_2^2 + z_{\varepsilon,m}^2) + 2a_3^2(I_{\text{ion}}^z)^2$$

and by (2.24) and Lemma 3.1, we can find a positive constant C such that

$$|\partial_t z_{\varepsilon,m}|^2 \leq C \left(1 + |z_{\varepsilon,m}|^2 + |v_{\varepsilon,m}|^2 + |\ln z_{\varepsilon,m}|^2 \right).$$

1 **Integrating the above inequality over Ω_T** and exploiting the estimates of Lemma 3.3 along with
 2 estimate (3.23), we obtain (3.33) for $z_{\varepsilon,m}$. Similarly, we get the $L^2(\Omega_T)$ uniform bound of $\partial_t \gamma_{\varepsilon,m}$.
 3 \square

4 **Lemma 3.7.** *There exist constants C_6 and $C_7 > 0$ independent of ε and m such that:*

$$\max_{t \in [0, T]} (\|\sqrt{\varepsilon} \mathbf{u}_{\varepsilon,m}\|_{L^2(\Omega)^3}^2 + \|\sqrt{\varepsilon} p_{\varepsilon,m}\|_{L^2(\Omega)}^2) + \|\mathbf{u}_{\varepsilon,m}\|_{L^2(0, T; H^1(\Omega)^3)} \leq C_6, \quad (3.34)$$

$$\|\varepsilon \partial_t p_{\varepsilon,m}\|_{L^2(0, T; (H^1(\Omega))')} + \|\varepsilon \partial_t \mathbf{u}_{\varepsilon,m}\|_{L^2(0, T; (H^1(\Omega)^3)')} \leq C_7. \quad (3.35)$$

Proof. Proof of (3.34):

In this proof, we first substitute $\psi_m := \mathbf{u}_{\varepsilon,m}$ and $\rho_m := p_{\varepsilon,m}$ in the first two equations of system (3.6) and we add them to obtain

$$\begin{aligned} \frac{\varepsilon}{2} \frac{d}{dt} \int_{\Omega} |\mathbf{u}_{\varepsilon,m}|^2 d\mathbf{x} + \int_{\Omega} (\nabla \mathbf{u}_{\varepsilon,m}) \boldsymbol{\sigma}(\mathbf{x}, \gamma_{\varepsilon,m}) : \nabla \mathbf{u}_{\varepsilon,m} d\mathbf{x} \\ + \frac{\varepsilon}{2} \frac{d}{dt} \int_{\Omega} |p_{\varepsilon,m}|^2 d\mathbf{x} + \alpha \int_{\partial\Omega} |\mathbf{u}_{\varepsilon,m}|^2 ds = \int_{\Omega} \mathbf{f} \cdot \mathbf{u}_{\varepsilon,m} d\mathbf{x}. \end{aligned}$$

Next, we define the continuous bilinear form

$$a(\mathbf{u}, \mathbf{v}) = \int_{\Omega} (\nabla \mathbf{u}) \boldsymbol{\sigma}(\mathbf{x}, \gamma) : \nabla \mathbf{v} d\mathbf{x} + \int_{\partial\Omega} \alpha \mathbf{u} \cdot \mathbf{v} ds.$$

5 Furthermore, we claim and we prove the following statement:

6 *Claim:* The bilinear form a is coercive on $(H^1(\Omega))^3$.

7 *Proof of Claim*

8 By the uniform ellipticity of $\boldsymbol{\sigma}$ (A.1), we have:

$$\begin{aligned} a(\mathbf{u}, \mathbf{u}) &= \int_{\Omega} (\nabla \mathbf{u}) \boldsymbol{\sigma} : \nabla \mathbf{u} d\mathbf{x} + \alpha \|\mathbf{u}\|_{L^2(\partial\Omega)}^2 \\ &\simeq \|\nabla \mathbf{u}\|^2 + \alpha \|\mathbf{u}\|_{L^2(\partial\Omega)}^2 \end{aligned}$$

We want to show that there exists $c > 0$ such that $c(\|\nabla \mathbf{u}\|_{(L^2(\Omega))^{3 \times 3}}^2 + \alpha \|\mathbf{u}\|_{L^2(\partial\Omega)}^2) \geq \|\mathbf{u}\|_{(H^1(\Omega))^3}$, $\forall \mathbf{u} \in (H^1(\Omega))^3$. We proceed by contradiction.

Assume that

$$\forall n > 0, \quad \exists \mathbf{u}_n \in (H^1(\Omega))^3 \text{ such that } \|\nabla \mathbf{u}_n\|_{(L^2(\Omega))^{3 \times 3}}^2 + \alpha \|\mathbf{u}_n\|_{L^2(\partial\Omega)}^2 \leq \frac{1}{n} \|\mathbf{u}_n\|_{(H^1(\Omega))^3}^2$$

and let $\mathbf{v}_n = \frac{\mathbf{u}_n}{\|\mathbf{u}_n\|_{(H^1(\Omega))^3}}$ so that $\|\mathbf{v}_n\|_{(H^1(\Omega))^3} = 1$ and

$$\|\nabla \mathbf{v}_n\|_{(L^2(\Omega))^{3 \times 3}}^2 + \alpha \|\mathbf{v}_n\|_{L^2(\partial\Omega)}^2 \leq \frac{1}{n},$$

9 which implies that

$$\nabla \mathbf{v}_n \rightarrow 0 \quad \text{in } (L^2(\Omega))^{3 \times 3}, \quad (3.36)$$

10 and

$$\mathbf{v}_n \rightarrow 0 \quad \text{in } (L^2(\partial\Omega))^3. \quad (3.37)$$

On the other hand, since \mathbf{v}_n is bounded in $(H^1(\Omega))^3$ and Ω is bounded and smooth, there exists $\mathbf{v} \in (H^1(\Omega))^3$ and a subsequence \mathbf{v}_{n_k} in $(H^1(\Omega))^3$ such that

$$\mathbf{v}_{n_k} \rightarrow \mathbf{v} \quad \text{in } (L^2(\Omega))^3$$

and

$$\nabla \mathbf{v}_{\mathbf{n}_k} \rightarrow \nabla \mathbf{v} \text{ in } \mathbf{D}'(\Omega).$$

Now using (3.36), we deduce that $\nabla \mathbf{v} = 0$, hence $\mathbf{v} = C$, since Ω is connected. Also, using (3.36) and the convergence of $\mathbf{v}_{\mathbf{n}_k}$ to C in $(L^2(\Omega))^3$, we obtain

$$\mathbf{v}_{\mathbf{n}_k} \rightarrow C \text{ in } (H^1(\Omega))^3$$

which implies by the continuity of the trace map γ_0 that

$$\gamma_0 \mathbf{v}_{\mathbf{n}_k} \rightarrow C \text{ in } (L^2(\partial\Omega))^3.$$

- 1 On the other hand, by (3.37), we have $\mathbf{v}_{\mathbf{n}_k} \rightarrow 0$ in $(L^2(\partial\Omega))^3$. So $C = 0$, hence we obtain a
 2 contradiction since $\|\mathbf{v}_{\mathbf{n}_k}\|_{(H^1(\Omega))^3} = 1$. \square
 3 By the coercivity of the bilinear form a and Young's inequality, we have

$$\frac{1}{2} \frac{d}{dt} \left(\|\sqrt{\varepsilon} \mathbf{u}_{\varepsilon,m}\|_{L^2(\Omega)^3}^2 + \|\sqrt{\varepsilon} p_{\varepsilon,m}\|_{L^2(\Omega)}^2 \right) + \frac{c}{2} \|\mathbf{u}_{\varepsilon,m}\|_{H^1(\Omega)^3}^2 \leq \frac{1}{2c} \|\mathbf{f}\|_{L^2(\Omega)}^2. \quad (3.38)$$

Integrating (3.38) over $(0, t)$ with $0 < t \leq T$, noting that $\mathbf{u}_{\varepsilon,m}(0) = 0$ and $\|p_{0,\varepsilon,m}\|_{L^2(\Omega)} \leq \|p_0\|_{L^2(\Omega)}$, we obtain

$$\|\sqrt{\varepsilon} \mathbf{u}_{\varepsilon,m}(t)\|_{L^2(\Omega)^3}^2 + \|\sqrt{\varepsilon} p_{\varepsilon,m}(t)\|_{L^2(\Omega)}^2 \leq c_{28} (\|\mathbf{f}\|_{L^2(\Omega_t)}^2 + \varepsilon \|p_0\|_{L^2(\Omega)}^2).$$

Hence,

$$\max_{t \in [0, T]} (\|\sqrt{\varepsilon} \mathbf{u}_{\varepsilon,m}\|_{L^2(\Omega)^3}^2 + \|\sqrt{\varepsilon} p_{\varepsilon,m}\|_{L^2(\Omega)}^2) \leq c_{29}.$$

- 4 We also have upon integration of (3.38)

$$c \int_0^T \|\mathbf{u}_{\varepsilon,m}(t)\|_{H^1(\Omega)^3}^2 \leq c_{30}(T) (\|\mathbf{f}\|_{L^2(\Omega_T)}^2 + \varepsilon \|p_0\|_{L^2(\Omega_T)}^2). \quad (3.39)$$

As a result, estimate (3.34) follows.

In order to obtain estimate (3.35), we let $\psi \in L^2(0, T; H^1(\Omega))$ and we take $\rho_m = \psi$ in (3.6) to get

$$\begin{aligned} \int_0^T |\langle \varepsilon \partial_t p_{\varepsilon,m}, \psi \rangle_{(H^1)', H^1}|^2 dt &= \int_0^T |(\partial_t p_{\varepsilon,m}, \psi)_{L^2}|^2 dt \\ &= \int_0^T |(\psi, \nabla \cdot \mathbf{u}_{\varepsilon,m})_{L^2}|^2 dt \\ &\leq \int_0^T \|\psi\|_{L^2}^2 \|\nabla \cdot \mathbf{u}_{\varepsilon,m}\|_{L^2}^2 dt \\ &\leq \|\mathbf{u}_{\varepsilon,m}\|_{L^2(0, T; H^1(\Omega)^3)}^2 \|\psi\|_{L^2(0, T; H^1(\Omega))}^2 \\ &\leq C_6 \|\psi\|_{L^2(0, T; H^1(\Omega))}^2. \end{aligned}$$

Similarly, we get

$$\int_0^T |\langle \varepsilon \partial_t \mathbf{u}_{\varepsilon,m}, \psi \rangle_{(H^1)', H^1}|^2 dt \leq C'_6 \|\psi\|_{L^2(0, T; H^1(\Omega))}^2,$$

- 5 for some constant $C'_6 > 0$. Therefore, estimate (3.35) follows directly.
 6 \square

7 **Remark 3.1.** We note that one can exploit the structure of the equations to obtain upper bounds
 8 on $\|\varepsilon \partial_t \mathbf{u}_{\varepsilon,m}\|_{L^1(0, T; (H^1(\Omega))')}$ and $\|p_{\varepsilon,m}\|_{L^1(0, T; L^2(\Omega))}$. With a wise choice of a sequence of test
 9 functions in $H_0^1(0, T)$ along with the Ladyzhenskaya-Babuška-Brezzi condition, we can bound $p_{\varepsilon,m}$
 10 in $L^1(0, T; L^2(\Omega))$ and consequently $\varepsilon \partial_t \mathbf{u}_{\varepsilon,m}$.

1 **3.3. Compactness properties and Convergence.** Having proved that the Faedo-Galerkin so-
 2 lutions (3.1) are well defined, we are ready to prove existence of solutions to the regularized
 3 system.

4 **Theorem 3.1.** *Assume (A.1)-(A.8) hold. Then the regularized system possesses a weak solution*
 5 *for each $\varepsilon > 0$.*

6 The remaining part of this subsection is devoted to proving Theorem 3.1.

7 In view of Lemma 3.5, we can construct subsequences of $v_{\varepsilon,m}$, $v_{i,\varepsilon,m}$, $v_{e,\varepsilon,m}$, $\mathbf{w}_{\varepsilon,m}$, $\gamma_{\varepsilon,m}$, $z_{\varepsilon,m}$,
 8 $\mathbf{u}_{\varepsilon,m}$, $p_{\varepsilon,m}$ which we do not bother to relabel, such that:

- 9 • $v_{\varepsilon,m} \rightharpoonup v_\varepsilon$, weakly in $L^2(0, T; H^1(\Omega))$,
- 10 • $\mathbf{w}_{\varepsilon,m} \rightharpoonup \mathbf{w}_\varepsilon$ weakly in $L^2(0, T; H^1(\Omega)^k)$ and $\partial_t \mathbf{w}_{\varepsilon,m} \rightharpoonup \partial_t \mathbf{w}_\varepsilon$ weakly in $(L^2(\Omega_T))^k$,
- 11 • $\gamma_{\varepsilon,m} \rightharpoonup \gamma_\varepsilon$ weakly in $L^2(0, T; H^1(\Omega))$ and $\partial_t \gamma_{\varepsilon,m} \rightharpoonup \partial_t \gamma_\varepsilon$ weakly in $L^2(\Omega_T)$,
- 12 • $z_{\varepsilon,m} \rightharpoonup z_\varepsilon$ weakly in $L^2(0, T; H^1(\Omega))$ and $\partial_t z_{\varepsilon,m} \rightharpoonup \partial_t z_\varepsilon$ weakly in $L^2(\Omega_T)$,
- 13 • $v_{i,\varepsilon,m} \rightharpoonup v_{i,\varepsilon}$ weakly in $L^2(0, T; H^1(\Omega))$ and $\nabla v_{i,\varepsilon,m} \rightharpoonup \nabla v_{i,\varepsilon}$ weakly in $L^2(\Omega_T)$,
- 14 • $v_{e,\varepsilon,m} \rightharpoonup v_{e,\varepsilon}$ weakly in $L^2(0, T; H^1(\Omega))$ and $\nabla v_{e,\varepsilon,m} \rightharpoonup \nabla v_{e,\varepsilon}$ weakly in $L^2(\Omega_T)$,
- 15 • $\mathbf{u}_{\varepsilon,m} \rightharpoonup \mathbf{u}_\varepsilon$ weakly in $L^2(0, T; H^1(\Omega)^3)$ and $\nabla \mathbf{u}_{\varepsilon,m} \rightharpoonup \nabla \mathbf{u}_\varepsilon$ weakly in $L^2(\Omega_T)^{3 \times 3}$,
- 16 • and $p_{\varepsilon,m} \rightharpoonup p_\varepsilon$ weak star in $L^\infty(0, T; L^2(\Omega))$ and weakly in $L^2(\Omega_T)$.

17 We also observe that from the sequences $U_{i,\varepsilon,m}$ and $U_{e,\varepsilon,m}$ introduced in the proof of Lemma
 18 3.5, we can extract subsequences such that:

$$19 \quad U_{i,\varepsilon,m} \rightharpoonup v_\varepsilon + \varepsilon v_{i,\varepsilon} \text{ in } L^2(0, T; H^1(\Omega)),$$

$$20 \quad U_{e,\varepsilon,m} \rightharpoonup v_\varepsilon - \varepsilon v_{e,\varepsilon} \text{ in } L^2(0, T; H^1(\Omega)).$$

21 Moreover, knowing that $\partial_t U_{i,\varepsilon,m}$ and $\partial_t U_{e,\varepsilon,m}$ are uniformly bounded in $L^2(0, T; (H^1(\Omega))')$, we
 22 obtain, by compactness and uniqueness of the limit, the following strong convergence:

$$23 \quad U_{i,\varepsilon,m} \rightarrow U_{i,\varepsilon} = v_\varepsilon + \varepsilon v_{i,\varepsilon} \text{ in } L^2(\Omega_T) \text{ and a.e. in } \Omega_T,$$

$$24 \quad U_{e,\varepsilon,m} \rightarrow U_{e,\varepsilon} := v_\varepsilon - \varepsilon v_{e,\varepsilon} \text{ in } L^2(\Omega_T) \text{ and a.e. in } \Omega_T.$$

25 As a result, $U_{i,\varepsilon,m} + U_{e,\varepsilon,m} = (1 + \varepsilon)v_{\varepsilon,m} \rightarrow U_{i,\varepsilon} + U_{e,\varepsilon} := (1 + \varepsilon)v_\varepsilon$ in $L^2(\Omega_T)$ and a.e. in Ω_T .
 26 Hence, $v_{\varepsilon,m} \rightarrow v_\varepsilon$ in $L^2(\Omega_T)$ and a.e. in Ω_T .

27 Also from classical compactness results, (see [37] Theorem 5.1 p58), we have

- 28 • $\mathbf{w}_{\varepsilon,m} \rightarrow \mathbf{w}_\varepsilon$ strongly in $L^2(\Omega_T)^k$ and a.e. in Ω_T ,
- 29 • $\gamma_{\varepsilon,m} \rightarrow \gamma_\varepsilon$ strongly in $L^2(\Omega_T)$ and a.e. in Ω_T ,
- 30 • $z_{\varepsilon,m} \rightarrow z_\varepsilon$ strongly in $L^2(\Omega_T)$ and a.e. in Ω_T ,

where $\mathbf{u}_\varepsilon \in L^2(0, T; H^1(\Omega)^3)$, $v_\varepsilon \in L^\infty(0, T; L^2(\Omega)) \cap L^2(0, T; H^1(\Omega))$, $\mathbf{w}_\varepsilon \in L^\infty(\Omega_T)^k \cap L^2(0, T; H^1(\Omega)^k)$,
 $\gamma_\varepsilon \in L^2(0, T; H^1(\Omega))$, $z_\varepsilon \in L^2(0, T; H^1(\Omega))$, and p_ε , in $L^\infty(0, T; L^2(\Omega))$. For $l \geq 1$ fixed,
 $j = 1, \dots, k$ and $\phi \in \mathcal{D}(0, T)$, we naturally have

$$\varepsilon \int_0^T \int_\Omega \partial_t \mathbf{u}_{\varepsilon,m} \psi_l \phi = -\varepsilon \int_0^T \int_\Omega \mathbf{u}_{\varepsilon,m} \psi_l \phi' \rightarrow -\varepsilon \int_0^T \int_\Omega \mathbf{u}_\varepsilon \psi_l \phi',$$

$$\varepsilon \int_0^T \int_\Omega \partial_t p_{\varepsilon,m} \psi_l \phi = -\varepsilon \int_0^T \int_\Omega p_{\varepsilon,m} \omega_l \phi' \rightarrow -\varepsilon \int_0^T \int_\Omega p_\varepsilon \omega_l \phi'.$$

As a consequence, we have in the space of distributions $\mathcal{D}'(0, T)$,

$$\varepsilon \int_\Omega \partial_t \mathbf{u}_{\varepsilon,m} \psi_l \rightarrow \varepsilon \int_\Omega \partial_t \mathbf{u}_\varepsilon \psi_l \text{ and } \varepsilon \int_\Omega \partial_t p_{\varepsilon,m} \omega_l \rightarrow \varepsilon \int_\Omega \partial_t p_\varepsilon \omega_l.$$

Since the electromechanical transmission is provided via variables $\gamma_{\varepsilon,m}$, $\mathbf{w}_{\varepsilon,m}$ and $z_{\varepsilon,m}$, we discuss
 first the passage to the limit in the governing ODE system.

We have $\mathbf{w}_{\varepsilon,m} \rightarrow \mathbf{w}_\varepsilon$ and $\gamma_{\varepsilon,m} \rightarrow \gamma_\varepsilon$ a.e. in Ω_T and S is continuous, so that $S(\gamma_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}) \rightarrow$
 $S(\gamma_\varepsilon, \mathbf{w}_\varepsilon)$ a.e. in Ω_T ; and $S(\gamma_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}) \rightharpoonup S(\gamma_\varepsilon, \mathbf{w}_\varepsilon)$ weakly in $L^2(\Omega_T)$ (being a linear continuous
 form on $L^2(\Omega_T) \times L^2(\Omega_T)^k$).

Using a classical result, see [37] Lemma 1.3 p 12, the continuity of $\mathbf{R}(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m})$ and its bound
 in $L^2(\Omega_T)$ (which is a consequence of assumption (A.6)), (2.21) and assertion (3.23)), yield the
 weak convergence $\mathbf{R}(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}) \rightharpoonup \mathbf{R}(v_\varepsilon, \mathbf{w}_\varepsilon)$ in $L^2(\Omega_T)^k$.

Similarly, by continuity of $G(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m})$ and its boundedness in $L^2(\Omega_T)$ (as a result of (3.14),
 and (3.23)), we obtain the weak convergence $G(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m}) \rightharpoonup G(v_\varepsilon, \mathbf{w}_\varepsilon, z_\varepsilon)$ in $L^2(\Omega_T)$.

The strong $L^2(\Omega_T)$ and a.e. Ω_T convergence of $\gamma_{\varepsilon,m}$ implies the strong and a.e. convergence of the uniformly bounded family of tensors $\boldsymbol{\sigma}(\mathbf{x}, \gamma_{\varepsilon,m})$, due to assumptions **(A.1)** and **(A.2)**. With this information, we can write for all $\varphi \in \mathcal{D}(0, T)$:

$$\begin{aligned} \int_0^T \langle \nabla \mathbf{u}_{\varepsilon,m} \boldsymbol{\sigma}(\mathbf{x}, \gamma_{\varepsilon,m}), \nabla \boldsymbol{\psi}_l \rangle_{L^2(\Omega), L^2(\Omega)} \varphi dt &= \int_0^T \langle \nabla \mathbf{u}_{\varepsilon,m} (\boldsymbol{\sigma}(\mathbf{x}, \gamma_{\varepsilon,m}) - \boldsymbol{\sigma}(\mathbf{x}, \gamma_\varepsilon)), \nabla \boldsymbol{\psi}_l \rangle \varphi dt \\ &\quad + \int_0^T \langle \nabla \mathbf{u}_{\varepsilon,m} \boldsymbol{\sigma}(\mathbf{x}, \gamma_\varepsilon), \nabla \boldsymbol{\psi}_l \rangle \varphi dt \\ &= \int_0^T \langle \nabla \mathbf{u}_{\varepsilon,m} (\boldsymbol{\sigma}(\mathbf{x}, \gamma_{\varepsilon,m}) - \boldsymbol{\sigma}(\mathbf{x}, \gamma_\varepsilon)), \nabla \boldsymbol{\psi}_l \rangle \varphi dt \\ &\quad + \int_0^T \langle \nabla \mathbf{u}_{\varepsilon,m}, \boldsymbol{\sigma}(\mathbf{x}, \gamma_\varepsilon) \nabla \boldsymbol{\psi}_l \rangle \varphi dt. \end{aligned}$$

The weak $L^2(\Omega_T)^{3 \times 3}$ convergence of $\nabla \mathbf{u}_{\varepsilon,m}$ directly implies the convergence of the last term on the right hand side to $\langle \nabla \mathbf{u}_\varepsilon, \boldsymbol{\sigma}(\mathbf{x}, \gamma_\varepsilon) \nabla \boldsymbol{\psi}_l \rangle = \langle \nabla \mathbf{u}_\varepsilon \boldsymbol{\sigma}(\mathbf{x}, \gamma_\varepsilon), \nabla \boldsymbol{\psi}_l \rangle$. It remains to prove that the first term converges to 0; we write

$$\begin{aligned} \int_0^T \langle \nabla \mathbf{u}_{\varepsilon,m} (\boldsymbol{\sigma}(\mathbf{x}, \gamma_{\varepsilon,m}) - \boldsymbol{\sigma}(\mathbf{x}, \gamma_\varepsilon)), \nabla \boldsymbol{\psi}_l \rangle |\varphi| dt \\ \leq \int_0^T \|\nabla \mathbf{u}_{\varepsilon,m}\|_{L^2} \|(\boldsymbol{\sigma}(\mathbf{x}, \gamma_{\varepsilon,m}) - \boldsymbol{\sigma}(\mathbf{x}, \gamma_\varepsilon)) \nabla \boldsymbol{\psi}_l\|_{L^2} |\varphi| dt \\ \leq \mathcal{C} \int_0^T \|(\boldsymbol{\sigma}(\mathbf{x}, \gamma_{\varepsilon,m}) - \boldsymbol{\sigma}(\mathbf{x}, \gamma_\varepsilon)) \nabla \boldsymbol{\psi}_l\|_{L^2} |\varphi| dt. \end{aligned}$$

Knowing that $(\boldsymbol{\sigma}(\mathbf{x}, \gamma_{\varepsilon,m}) - \boldsymbol{\sigma}(\mathbf{x}, \gamma_\varepsilon)) \nabla \boldsymbol{\psi}_l \rightarrow 0$ a.e. in Ω and a.e. in $(0, T)$ and that $|(\boldsymbol{\sigma}(\mathbf{x}, \gamma_{\varepsilon,m}) - \boldsymbol{\sigma}(\mathbf{x}, \gamma_\varepsilon)) \nabla \boldsymbol{\psi}_l|$ is (due to assumption **(A.1)**) bounded by a constant multiple of $|\nabla \boldsymbol{\psi}_l| \in L^2(\Omega)$ for a.e. $t \in (0, T)$, we can apply Lebesgue's dominated convergence theorem to obtain $\|[\boldsymbol{\sigma}(\cdot, \gamma_{\varepsilon,m}) - \boldsymbol{\sigma}(\cdot, \gamma_\varepsilon)] \nabla \boldsymbol{\psi}_l\|_{L^2(\Omega)} \rightarrow 0$ for a.e. $t \in (0, T)$. Similarly, one can apply Lebesgue's dominated convergence theorem on $(0, T)$ to reach the required result.

The remaining term in the elasticity equation involves $\mathbf{f}(t, \mathbf{x}, \gamma_{\varepsilon,m})$, by (2.9) and assumption **(A.2)** we obtain the a.e. convergence of $\mathbf{f}(t, \mathbf{x}, \gamma_{\varepsilon,m})$ from the a.e. convergence of $\gamma_{\varepsilon,m}$ in Ω_T . Furthermore, by assumption **(A.8)** and estimate (3.32) we get:

$$\int_0^T \int_\Omega \mathbf{f}(t, \mathbf{x}, \gamma_{\varepsilon,m}) \cdot \boldsymbol{\psi}_l \phi(t) \rightarrow \int_0^T \int_\Omega \mathbf{f}(t, \mathbf{x}, \gamma_\varepsilon) \cdot \boldsymbol{\psi}_l \phi(t), \quad \forall \phi \in \mathcal{D}(0, T).$$

In order to pass to the limit in the electrical part of the system, the strong L^2 convergence of the gradients $\nabla \mathbf{u}_{\varepsilon,m}$ is needed. Indeed, since the limit \mathbf{u} solves the limit equation of (3.2), using the Minty-Browder trick (see, e.g. [38, 37, 39]), we are able to assert that $\nabla \mathbf{u}_{\varepsilon,m} \rightarrow \nabla \mathbf{u}_\varepsilon$ strongly in $(L^2(\Omega_T))^{3 \times 3}$. Indeed, one can also exploit the structure of the elasticity equations and the

coercivity of the bilinear form a to obtain

$$\begin{aligned}
\frac{1}{c} \|\mathbf{u}_{\varepsilon,m} - \mathbf{u}_\varepsilon\|_{L^2(0,T;H^1(\Omega)^3)}^2 &\leq \int_0^T a(\mathbf{u}_{\varepsilon,m} - \mathbf{u}_\varepsilon, \mathbf{u}_{\varepsilon,m} - \mathbf{u}_\varepsilon) dt \\
&= - \int_0^T \langle \varepsilon \partial_t (\mathbf{u}_{\varepsilon,m} - \mathbf{u}_\varepsilon), \mathbf{u}_{\varepsilon,m} - \mathbf{u}_\varepsilon \rangle dt - \varepsilon \|p_{\varepsilon,m}(T) - p_\varepsilon(T)\|_{L^2(\Omega_T)}^2 \\
&\quad + \varepsilon \|p_{\varepsilon,m}(0) - p_0\|_{L^2(\Omega_T)}^2 \\
&\quad - \int_{\Omega_T} \nabla \mathbf{u}_\varepsilon [\boldsymbol{\sigma}(\mathbf{x}, \gamma_{\varepsilon,m}) - \boldsymbol{\sigma}(\mathbf{x}, \gamma_\varepsilon)] : \nabla (\mathbf{u}_{\varepsilon,m} - \mathbf{u}_\varepsilon) d\mathbf{x} dt \\
&\quad - \int_{\Omega_T} [f(\mathbf{x}, \gamma_{\varepsilon,m}) - f(\mathbf{x}, \gamma_\varepsilon)] \cdot (\mathbf{u}_{\varepsilon,m} - \mathbf{u}_\varepsilon) d\mathbf{x} dt \\
&\leq - \int_0^T \langle \varepsilon \partial_t (\mathbf{u}_{\varepsilon,m} - \mathbf{u}_\varepsilon), \mathbf{u}_{\varepsilon,m} - \mathbf{u}_\varepsilon \rangle dt + \varepsilon \|p_{\varepsilon,m}(0) - p_0\|_{L^2(\Omega_T)}^2 \\
&\quad - \int_{\Omega_T} \nabla \mathbf{u}_\varepsilon [\boldsymbol{\sigma}(\mathbf{x}, \gamma_{\varepsilon,m}) - \boldsymbol{\sigma}(\mathbf{x}, \gamma_\varepsilon)] : \nabla (\mathbf{u}_{\varepsilon,m} - \mathbf{u}_\varepsilon) d\mathbf{x} dt \\
&\quad - \int_{\Omega_T} [f(\mathbf{x}, \gamma_{\varepsilon,m}) - f(\mathbf{x}, \gamma_\varepsilon)] \cdot (\mathbf{u}_{\varepsilon,m} - \mathbf{u}_\varepsilon) d\mathbf{x} dt.
\end{aligned}$$

Exploiting the convergence results obtained above along with the strong convergence of $p_{\varepsilon,m}(0)$ to p_0 and assumptions (A.1) and (A.2), one can show that the right hand side of the last inequality goes to 0 as $m \rightarrow \infty$. Therefore, $\nabla \mathbf{u}_{\varepsilon,m} \rightarrow \nabla \mathbf{u}_\varepsilon$ strongly in $L^2(\Omega_T)^{3 \times 3}$.

Due to assumptions (A.3)-(A.4), strong convergence of $\nabla \mathbf{u}_{\varepsilon,m}$ implies a.e. convergence of $\mathbf{M}_{i,e}(\mathbf{x}, \nabla \mathbf{u}_{\varepsilon,m})$ to the limit $\mathbf{M}_{i,e}(\mathbf{x}, \nabla \mathbf{u}_\varepsilon)$; hence we can use again the dominated convergence argument to obtain $\forall \phi \in \mathcal{D}(0, T)$ and for $k = i, e$

$$\int_0^T \int_\Omega \mathbf{M}_k(\mathbf{x}, \nabla \mathbf{u}_{\varepsilon,m}) \nabla v_{k,\varepsilon,m} \cdot \nabla \omega_l \phi(t) \rightarrow \int_0^T \int_\Omega \mathbf{M}_k(\mathbf{x}, \nabla \mathbf{u}_\varepsilon) \nabla v_{k,\varepsilon} \cdot \nabla \omega_l \phi(t).$$

Moreover, observe that I_{ion} is a continuous function of $v_{\varepsilon,m}$, $\mathbf{w}_{\varepsilon,m}$, $z_{\varepsilon,m}$, and that it is uniformly bounded in $L^2(\Omega_T)$, again by standard arguments we have

$$\int_0^T \int_\Omega I_{\text{ion}}(v_{\varepsilon,m}, \mathbf{w}_{\varepsilon,m}, z_{\varepsilon,m}) \omega_l \phi(t) \rightarrow \int_0^T \int_\Omega I_{\text{ion}}(v_\varepsilon, \mathbf{w}_\varepsilon, z_\varepsilon) \omega_l \phi(t), \quad \forall \phi \in \mathcal{D}(0, T).$$

- 1 Gathering all these results, the functions $\mathbf{u}_\varepsilon, p_\varepsilon, v_\varepsilon, v_{i,\varepsilon}, v_{e,\varepsilon}, \gamma_\varepsilon, \mathbf{w}_\varepsilon, z_\varepsilon$ verify in the space of distributions $\mathcal{D}'(0, T)$, for all functions $\boldsymbol{\psi} \in H^1(\Omega)^3, \rho \in L^2(\Omega), \omega \in H^1(\Omega)$, and $\mu \in H^{1,0}(\Omega)$:

$$\begin{aligned}
\langle \varepsilon \partial_t \mathbf{u}_\varepsilon, \boldsymbol{\psi} \rangle + \int_\Omega (\nabla \mathbf{u}_\varepsilon) \boldsymbol{\sigma}(\mathbf{x}, \gamma_\varepsilon) : \nabla \boldsymbol{\psi} - p_\varepsilon \nabla \cdot \boldsymbol{\psi} d\mathbf{x} + \int_{\partial\Omega} \alpha \mathbf{u}_\varepsilon \cdot \boldsymbol{\psi} ds &= \int_\Omega \mathbf{f} \cdot \boldsymbol{\psi} d\mathbf{x} \\
\langle \varepsilon p'_\varepsilon, \rho \rangle + \int_\Omega \rho \nabla \cdot \mathbf{u}_\varepsilon &= 0 \\
\langle \partial_t v_\varepsilon + \varepsilon \partial_t v_{i,\varepsilon}, \omega \rangle + \int_\Omega (\mathbf{M}_i(\mathbf{x}, \nabla \mathbf{u}_\varepsilon) \nabla v_{i,\varepsilon} \cdot \nabla \omega + I_{\text{ion}}(v_\varepsilon, \mathbf{w}_\varepsilon, z_\varepsilon) \omega) d\mathbf{x} &= \int_\Omega I_i^s \omega d\mathbf{x} \\
\langle \partial_t v_\varepsilon - \varepsilon \partial_t v_{e,\varepsilon}, \mu \rangle - \int_\Omega (\mathbf{M}_e(\mathbf{x}, \mathbf{u}_\varepsilon) \nabla v_{e,\varepsilon} \cdot \nabla \mu + I_{\text{ion}}(v_\varepsilon, \mathbf{w}_\varepsilon, z_{\varepsilon,m}) \mu) d\mathbf{x} &= \int_\Omega I_e^s \mu d\mathbf{x} \quad (3.40) \\
\forall j = 1, \dots, k, \int_\Omega \partial_t w_{j,\varepsilon} \omega &= \int_\Omega R_j(v_\varepsilon, \mathbf{w}_\varepsilon) \omega \\
\int_\Omega \partial_t z_\varepsilon \omega &= \int_\Omega G(v_\varepsilon, \mathbf{w}_\varepsilon, z_\varepsilon) \omega \\
\int_\Omega \partial_t \gamma_\varepsilon \omega &= \int_\Omega S(\gamma_\varepsilon, \mathbf{w}_\varepsilon, z_\varepsilon) \omega.
\end{aligned}$$

- 3 Finally, having $\mathbf{u}_\varepsilon \in L^2(0, T; H^1(\Omega)^3)$, $U_{i,e,\varepsilon}, \gamma_\varepsilon, z_\varepsilon \in L^2(0, T; H^1(\Omega))$, $\mathbf{w}_\varepsilon \in L^2(0, T; H^1(\Omega)^k)$ and $p_\varepsilon \in L^\infty(0, T; L^2(\Omega))$, and their weak derivatives $\partial_t \mathbf{u}_\varepsilon \in L^2(0, T; (H^1(\Omega)')^3)$, $\partial_t U_{i,e,\varepsilon}$, $\partial_t p_\varepsilon$ in $L^2(0, T; (H^1(\Omega)'))'$, $\partial_t \mathbf{w}_\varepsilon$ in $L^2(\Omega_T)^k$ and $\partial_t \gamma_\varepsilon, \partial_t z_\varepsilon$ in $L^2(\Omega_T)$, it is deduced from a classical result, that the functions $\mathbf{u}_\varepsilon : t \in [0, T] \mapsto \mathbf{u}_\varepsilon(t) \in H^1(\Omega)^3$, $U_{i,e,\varepsilon} : t \in [0, T] \mapsto U_{i,e,\varepsilon}(t) \in H^1(\Omega)$, $\mathbf{w}_\varepsilon : t \in [0, T] \mapsto \mathbf{w}_\varepsilon(t) \in L^2(\Omega)^k$, $\gamma_\varepsilon : t \in [0, T] \mapsto \gamma_\varepsilon(t) \in L^2(\Omega)$, and $z_\varepsilon : t \in [0, T] \mapsto z_\varepsilon(t) \in L^2(\Omega)$ are continuous. For p_ε , it only proves that they are weakly continuous in $H^1(\Omega)$.
- 9 Furthermore, since $\mathbf{u}_{\varepsilon,m}(0) \rightarrow \mathbf{u}_0$, $p_{\varepsilon,m}(0) \rightarrow p_0$, $v_{\varepsilon,m}(0) \rightarrow v_0$, $v_{k,\varepsilon,m}(0) \rightarrow v_{k,0}$, $k = i, e$,

1 $\mathbf{w}_{\varepsilon,m}(0) \rightarrow \mathbf{w}_0$, $\gamma_{\varepsilon,m}(0) \rightarrow \gamma_0$ and $z_{\varepsilon,m}(0) \rightarrow z_0$ in $L^2(\Omega)$, we easily prove that $\mathbf{u}_\varepsilon(0) = \mathbf{u}_0$,
 2 $p_\varepsilon(0) = p_0$, $v_\varepsilon(0) = v_0$, $v_{k,\varepsilon}(0) = v_{k,0}$, $k = i, e$, $\mathbf{w}_\varepsilon(0) = \mathbf{w}_0$, $\gamma_\varepsilon(0) = \gamma_0$ and $z_\varepsilon(0) = z_0$. The proof
 3 is by a standard argument given in [39] and one can refer to [3] for further details.

4. EXISTENCE OF SOLUTION TO THE ORIGINAL PROBLEM

5 From the previous section, we know there exist sequences $\{\mathbf{u}_\varepsilon\}_{\varepsilon>0}$, $\{p_\varepsilon\}_{\varepsilon>0}$, $\{v_\varepsilon\}_{\varepsilon>0}$, $\{v_{i,\varepsilon}\}_{\varepsilon>0}$, $\{v_{e,\varepsilon}\}_{\varepsilon>0}$,
 6 $\{\mathbf{w}_\varepsilon\}_{\varepsilon>0}$, $\{\gamma_\varepsilon\}_{\varepsilon>0}$, and $\{z_\varepsilon\}_{\varepsilon>0}$ of solutions of (3.40). Moreover, by the lower semicontinuity of
 7 norms, the following a priori estimates are immediately obtained as in Lemma 3.5 with $\mathbf{u}_{\varepsilon,m}$, $p_{\varepsilon,m}$,
 8 $v_{\varepsilon,m}$, $v_{i,\varepsilon,m}$, $v_{e,\varepsilon,m}$, $\mathbf{w}_{\varepsilon,m}$, $\gamma_{\varepsilon,m}$, $z_{\varepsilon,m}$ replaced by \mathbf{u}_ε , p_ε , v_ε , $v_{i,\varepsilon}$, $v_{e,\varepsilon}$, \mathbf{w}_ε , γ_ε , z_ε , respectively.

9 **Lemma 4.1.** *There exist constants $\mathcal{C}_1, \dots, \mathcal{C}_6$ independent of ε such that*

$$\max_{t \in [0, T]} \left(\|v_\varepsilon(t)\|_{L^2(\Omega)}^2 + \sum_{j=i,e} \|\sqrt{\varepsilon} v_{j,\varepsilon}\|_{L^2(\Omega)}^2 \right) \leq \mathcal{C}_1, \quad \forall t \in [0, T], \quad (4.1)$$

$$\left(\sum_{j=i,e} \|v_{i,\varepsilon}\|_{L^2(0, T; H^1(\Omega))} + \|v_\varepsilon\|_{L^2(0, T; H^1(\Omega))} \right) \leq \mathcal{C}_2, \quad (4.2)$$

$$\|\partial_t(v_\varepsilon + \varepsilon v_{i,\varepsilon})\|_{L^2(0, T; (H^1)'\Omega)} + \|\partial_t(v_\varepsilon - \varepsilon v_{e,\varepsilon})\|_{L^2(0, T; (H^1)'\Omega)} \leq \mathcal{C}_3, \quad (4.3)$$

$$\|\mathbf{w}_\varepsilon\|_{L^2(0, T; H^1(\Omega)^k)} + \|z_\varepsilon\|_{L^2(0, T; H^1(\Omega))} + \|\gamma_\varepsilon\|_{L^2(0, T; H^1(\Omega))} \leq \mathcal{C}_4, \quad (4.4)$$

$$\|\partial_t \mathbf{w}_\varepsilon\|_{L^2(\Omega_T)^k} + \|\partial_t z_\varepsilon\|_{L^2(\Omega_T)} + \|\partial_t \gamma_\varepsilon\|_{L^2(\Omega_T)} \leq \mathcal{C}_5, \quad (4.5)$$

$$\max_{t \in [0, T]} \left(\|\sqrt{\varepsilon} \mathbf{u}_\varepsilon\|_{L^2(\Omega)^3}^2 + \|\sqrt{\varepsilon} p_\varepsilon\|_{L^2(\Omega)}^2 \right) + \|\mathbf{u}_\varepsilon\|_{L^2(0, T; H^1(\Omega)^3)} \leq \mathcal{C}_6. \quad (4.6)$$

10 In view of Lemma 4.1, we can assume there exist limit functions \mathbf{u} , p , v , v_i , v_e , with $v = v_i - v_e$,
 11 \mathbf{w} , γ and z such that as $\varepsilon \rightarrow 0$, we can extract subsequences (which we do not bother to relabel)
 12 with the following convergence properties:

- 13 • $v_\varepsilon \rightarrow v$ strongly in $L^2(\Omega_T)$ and a.e. in Ω_T and weakly in $L^2(0, T; H^1(\Omega))$,
- 14 • $v_{i,\varepsilon} \rightarrow v_i$ weakly in $L^2(0, T; H^1(\Omega))$, $v_{e,\varepsilon} \rightarrow v_e$ weakly in $L^2(0, T; H^1(\Omega))$,
- 15 • $\mathbf{w}_\varepsilon \rightarrow \mathbf{w}$ strongly in $L^2(\Omega_T)^k$ and a.e. in Ω_T ,
- 16 • $\gamma_\varepsilon \rightarrow \gamma$ strongly in $L^2(\Omega_T)$ and a.e. in Ω_T ,
- 17 • $z_\varepsilon \rightarrow z$ strongly in $L^2(\Omega_T)$ and a.e. in Ω_T ,
- 18 • $\mathbf{u}_\varepsilon \rightharpoonup \mathbf{u}$ weakly in $L^2(0, T; H^1(\Omega)^3)$ and $\nabla \mathbf{u}_\varepsilon \rightharpoonup \nabla \mathbf{u}$ in $L^2(\Omega_T)^{3 \times 3}$.

We briefly note that in the distribution sense

$$\varepsilon \langle \partial_t \mathbf{u}_\varepsilon, \boldsymbol{\psi} \rangle \rightarrow 0,$$

in $\mathcal{D}'(0, T)$. Similarly,

$$\varepsilon \langle \partial_t p_\varepsilon, \psi \rangle \rightarrow 0,$$

19 in $\mathcal{D}'(0, T)$.

21 **Remark 4.1. Recuperation of p**

22 *Due to the ‘‘artificial compressibility’’ used in the proof, we were not able to obtain a bound on*
 23 *$\partial_t p_\varepsilon$ that is independent of ε except in $L^1(0, T; L^2(\Omega))$, (see remark 3.1), which is not a reflexive*
 24 *space. So in order to pass to the limit in the term involving the pressure, we made a detour by*
 25 *exploiting the structure of the equation and making use of De Rham’s Lemma. It is important*
 26 *to note that the boundary condition used herein (2.18) determines p uniquely and not up to an*
 27 *additive constant.*

28 Now we recall the following standard lemma (see for instance Theorem IV.3.1 p 245 in [40], see
 29 also [41, 42]).

30 **Lemma 4.2.** $\forall q \in L^2_0(\Omega) := \{q \in L^2(\Omega) : \int_\Omega q \, dx = 0\}$, there exists $\mathbf{v} \in (H^1_0(\Omega))^3$ such that
 31 $\nabla \cdot \mathbf{v} = q$.

32 This lemma will be used to prove the following result.

Lemma 4.3. *There exists $p \in L^2(\Omega_T)$ such that for a.e. $t \in (0, T)$ and for all $v \in (H^1(\Omega))^3$*

$$\int_{\Omega} p_{\varepsilon} \nabla \cdot v \rightarrow \int_{\Omega} p \nabla \cdot v.$$

Proof. For all $\mathbf{v} \in (\mathcal{D}(\Omega))^3$ with $\nabla \cdot \mathbf{v} = 0$ we have

$$\varepsilon \langle \partial_t \mathbf{u}_{\varepsilon}, \mathbf{v} \rangle + \int_{\Omega} (\nabla \mathbf{u}_{\varepsilon}) \boldsymbol{\sigma}(\mathbf{x}, \gamma_{\varepsilon}) : \nabla \mathbf{v} \, d\mathbf{x} = \int_{\Omega} \mathbf{f} \cdot \mathbf{v} \, d\mathbf{x}$$

Passing to the limit in ε we get

$$\int_{\Omega} (\nabla \mathbf{u}) \boldsymbol{\sigma}(\mathbf{x}, \gamma) : \nabla \mathbf{v} \, d\mathbf{x} = \int_{\Omega} \mathbf{f} \cdot \mathbf{v} \, d\mathbf{x}$$

Therefore, by de Rham's Lemma (see Theorem IV.2.5 in [40], see also [43, 44, 45, 46]), there exists, up to an additive constant, $p \in \mathcal{D}'(\Omega)$ such that

$$\nabla \cdot (\nabla \mathbf{u}) \boldsymbol{\sigma}(\mathbf{x}, \gamma) + \mathbf{f} = \nabla p$$

in the distribution sense. Moreover, by Nečas inequality (see Theorem IV.1.1 in [40], see also [47, 48, 46]), for a.e. $t \in (0, T)$, $p \in L^2(\Omega)$ since $\mathbf{u} \in (H^1(\Omega))^3$. Hence, $p \in L^2(\Omega_T)$.

Now we have, for all $\mathbf{v} \in (H_0^1(\Omega))^3$,

$$\int_{\Omega} p_{\varepsilon} \nabla \cdot \mathbf{v} \, d\mathbf{x} = \varepsilon \int_{\Omega} \partial_t \mathbf{u}_{\varepsilon} \cdot \mathbf{v} + \int_{\Omega} (\nabla \mathbf{u}_{\varepsilon}) \boldsymbol{\sigma}(\mathbf{x}, \gamma_{\varepsilon}) : \nabla \mathbf{v} \, d\mathbf{x} - \int_{\Omega} \mathbf{f} \cdot \mathbf{v} \, d\mathbf{x}$$

and

$$\int_{\Omega} p \nabla \cdot \mathbf{v} \, d\mathbf{x} = \int_{\Omega} (\nabla \mathbf{u}) \boldsymbol{\sigma}(\mathbf{x}, \gamma) : \nabla \mathbf{v} \, d\mathbf{x} - \int_{\Omega} \mathbf{f} \cdot \mathbf{v} \, d\mathbf{x}$$

Subtracting these two equations, we obtain

$$\int_{\Omega} (p_{\varepsilon} - p) \nabla \cdot \mathbf{v} \, d\mathbf{x} = \varepsilon \int_{\Omega} \partial_t \mathbf{u}_{\varepsilon} \cdot \mathbf{v} + \int_{\Omega} \left((\nabla \mathbf{u}_{\varepsilon}) \boldsymbol{\sigma}(\mathbf{x}, \gamma_{\varepsilon}) - (\nabla \mathbf{u}) \boldsymbol{\sigma}(\mathbf{x}, \gamma) \right) : \nabla \mathbf{v} \, d\mathbf{x}$$

1 Consequently, we get, for all $\mathbf{v} \in (H_0^1(\Omega))^3$,

$$\lim_{\varepsilon \rightarrow 0} \int_{\Omega} (p_{\varepsilon} - p) \nabla \cdot \mathbf{v} \, d\mathbf{x} = 0. \quad (4.7)$$

Thus, $\nabla p_{\varepsilon} \rightarrow \nabla p$ in $H^{-1}(\Omega)$.

In order to complete the passage to the limit and obtain the original weak formulation, it remains to get the following result:

$$\lim_{\varepsilon \rightarrow 0} \int_{\Omega} (p_{\varepsilon} - p) \nabla \cdot \mathbf{v} \, d\mathbf{x} = 0 \quad \text{for all } \mathbf{v} \in H^1(\Omega).$$

Let $q \in L^2(\Omega)$, set $\tilde{q} = q - C$ where $C = \frac{1}{|\Omega|} \int_{\Omega} q \, d\mathbf{x}$, so $\tilde{q} \in L_0^2(\Omega)$. By Lemma 4.2, there exists

$\tilde{\mathbf{v}} \in (H_0^1(\Omega))^3$ such that $\nabla \cdot \tilde{\mathbf{v}} = \tilde{q}$.

By Equation (4.7), we have

$$\lim_{\varepsilon \rightarrow 0} \int_{\Omega} (p_{\varepsilon} - p) \tilde{q} \, d\mathbf{x} = 0$$

In other words,

$$\int_{\Omega} (p_{\varepsilon} - p) q \, d\mathbf{x} - C \int_{\Omega} (p_{\varepsilon} - p) \, d\mathbf{x} \rightarrow 0 \quad \text{as } \varepsilon \rightarrow 0$$

So in order to obtain $\int_{\Omega} (p_{\varepsilon} - p) q \, d\mathbf{x} \rightarrow 0$, it is sufficient to show $\int_{\Omega} (p_{\varepsilon} - p) \, d\mathbf{x} \rightarrow 0$.

In fact, by the first equation of (3.40) we have for all $\mathbf{v} \in (H^1(\Omega))^3$,

$$\lim_{\varepsilon \rightarrow 0} \int_{\Omega} p_{\varepsilon} \nabla \cdot \mathbf{v} \, d\mathbf{x} = \int_{\Omega} (\nabla \mathbf{u}) \boldsymbol{\sigma}(\mathbf{x}, \gamma) : \nabla \mathbf{v} + \int_{\partial\Omega} \alpha \mathbf{u} \cdot \mathbf{v} \, ds - \int_{\Omega} \mathbf{f} \cdot \mathbf{v} \, d\mathbf{x}.$$

In particular, we can consider the test function $\mathbf{v}_1 = (x_1, 0, 0)$ which is in $(H^1(\Omega))^3$ and verifies $\nabla \cdot \mathbf{v}_1 = 1$. Thus we obtain

$$\lim_{\varepsilon \rightarrow 0} \int_{\Omega} p_{\varepsilon} d\mathbf{x} = \tilde{\mathcal{C}} := \int_{\Omega} (\nabla \mathbf{u}) \boldsymbol{\sigma}(\mathbf{x}, \gamma) : \nabla \mathbf{v}_1 + \int_{\partial\Omega} \alpha \mathbf{u} \cdot \mathbf{v}_1 ds - \int_{\Omega} \mathbf{f} \cdot \mathbf{v}_1 d\mathbf{x}.$$

Since by De Rham's Lemma, p is found up to an additive constant, then we choose it so that we have $\int_{\Omega} p d\mathbf{x} = \tilde{\mathcal{C}}$. Therefore, we have

$$\lim_{\varepsilon \rightarrow 0} \int_{\Omega} p_{\varepsilon} d\mathbf{x} = \tilde{\mathcal{C}} = \int_{\Omega} p d\mathbf{x}.$$

Consequently, we have, for all $q \in L^2(\Omega)$,

$$\lim_{\varepsilon \rightarrow 0} \int_{\Omega} (p_{\varepsilon} - p)q d\mathbf{x} = 0.$$

1

□

2 Therefore, according to all of the preceding convergence results, and repeating some of the
 3 arguments of the previous section, we have for all $\boldsymbol{\psi} \in H^1(\Omega)^3$, ρ in $L^2(\Omega)$, $\mu \in H^{1,0}(\Omega)$ (given as
 4 in Definition 2.1) and ω in $H^1(\Omega)$:

$$\begin{aligned} \int_{\Omega} (\nabla \mathbf{u}) \boldsymbol{\sigma}(\mathbf{x}, \gamma) : \nabla \boldsymbol{\psi} - p \nabla \cdot \boldsymbol{\psi} d\mathbf{x} + \int_{\partial\Omega} \alpha \mathbf{u} \cdot \boldsymbol{\psi} ds &= \int_{\Omega} \mathbf{f} \cdot \boldsymbol{\psi} d\mathbf{x} \\ & \int_{\Omega} \rho \nabla \cdot \mathbf{u} = 0 \\ \langle \partial_t v, \omega \rangle + \int_{\Omega} (\mathbf{M}_i(\mathbf{x}, \nabla \mathbf{u}_{\varepsilon, m}) \nabla v_i \cdot \nabla \omega + I_{\text{ion}}(v, \mathbf{w}, z) \omega) d\mathbf{x} &= \int_{\Omega} I_i^s \omega d\mathbf{x} \\ \langle \partial_t v, \mu \rangle - \int_{\Omega} (\mathbf{M}_e(\mathbf{x}, \nabla \mathbf{u}_{\varepsilon, m}) \nabla v_e \cdot \nabla \mu + I_{\text{ion}}(v, \mathbf{w}, z) \mu) d\mathbf{x} &= \int_{\Omega} I_e^s \mu d\mathbf{x} \quad (4.8) \\ \forall j = 1, \dots, k, \quad \int_{\Omega} \partial_t w_j \omega &= \int_{\Omega} R_j(v, \mathbf{w}) \omega \\ \int_{\Omega} \partial_t z \omega &= \int_{\Omega} G(v, \mathbf{w}, z) \omega \\ \int_{\Omega} \partial_t \gamma \omega &= \int_{\Omega} S(\gamma, \mathbf{w}, z) \omega. \end{aligned}$$

5 Repeating the argument of the previous section, the functions $v : t \in [0, T] \mapsto v(t) \in H^1(\Omega)$,
 6 $\mathbf{w} : t \in [0, T] \mapsto \mathbf{w}(t) \in L^2(\Omega)^k$, $\gamma : t \in [0, T] \mapsto \gamma(t) \in L^2(\Omega)$, and $z : t \in [0, T] \mapsto z(t) \in L^2(\Omega)$
 7 are continuous and satisfy the initial conditions $v(0, \mathbf{x}) = v_0(\mathbf{x})$, $\mathbf{w}(0, \mathbf{x}) = \mathbf{w}_0(\mathbf{x})$, $\gamma(0, \mathbf{x}) = \gamma_0(\mathbf{x})$
 8 and $z(0) = z_0(\mathbf{x})$.

9

5. CONCLUDING REMARKS

10 In summary, we consider that in our work, we have paved the way towards addressing the
 11 solvability of cardiac electromechanics coupled with physiological ionic models. We used a mathe-
 12 matical model (partially introduced in [27]) for the study of cardiac electromechanical interactions
 13 written in fully Lagrangian form, with a linearized description of the passive elastic response of
 14 cardiac tissue, a linearized incompressibility constraint, and a truncated approximation of the
 15 nonlinear diffusivities appearing in the bidomain equations. The existence proof is done using
 16 nondegenerate approximation systems, the Faedo-Galerkin method followed by a compactness
 17 argument. The model simplifications are used herein for the sake of the mathematical analysis
 18 but more realistic formulations have been addressed numerically. To conclude, deeper theoretical
 19 insight is needed to mathematically analyze more realistic models.

REFERENCES

1

- 2 [1] L. Tung. *A bi-domain model for describing ischemic myocardial D-C potentials*. PhD thesis, MIT, 1978.
- 3 [2] P. Colli Franzone and G. Savaré. Degenerate evolution systems modeling the cardiac electric field at micro-
4 and macroscopic level. In *Evolution equations, semigroups and functional analysis (Milano, 2000)*, volume 50
5 of *Progr. Nonlinear Differential Equations Appl.*, pages 49–78. Birkhäuser, 2002.
- 6 [3] M. Bendahmane and K.H. Karlsen. Analysis of a class of degenerate reaction-diffusion systems and the bidomain
7 model of cardiac tissue. *Netw. Heterog. Media*, 1(1):185–218, 2006.
- 8 [4] Y. Bourgault, Y. Coudière, and C. Pierre. Existence and uniqueness of the solution for the bidomain model
9 used in cardiac electrophysiology. *Nonl. Anal.: Real World Appl.*, 10(1):458–482, 2009.
- 10 [5] H. Matano and Y. Mori. Global existence and uniqueness of a three-dimensional model of cellular electrophysiology.
11 *Discrete Contin. Dyn. Syst.*, 29(4):1573–1636, 2011.
- 12 [6] M. Veneroni. Reaction–diffusion systems for the macroscopic bidomain model of the cardiac electric field. *Nonl.*
13 *Anal.: Real World Appl.*, 10(2):849–868, 2009.
- 14 [7] S. Göktepe and E. Kuhl. Electromechanics of the heart: a unified approach to the strongly coupled excitation–
15 contraction problem. *Comput. Mech.*, 45(2-3):227–243, 2010.
- 16 [8] P. Lafortune, R. Arís, M. Vázquez, and G. Houzeaux. Coupled electromechanical model of the heart: Parallel
17 finite element formulation. *Int. J. Numer. Methods Biomed. Engrg.*, 28(1):72–86, 2012.
- 18 [9] M.P. Nash and P.J. Hunter. Computational mechanics of the heart. From tissue structure to ventricular
19 function. *J. Elasticity*, 61(1-3):113–141, 2000.
- 20 [10] M.P. Nash and A.V. Panfilov. Electromechanical model of excitable tissue to study reentrant cardiac arrhythmias.
21 *Progr. Biophys. Molec. Biol.*, 85(23):501–522, 2004.
- 22 [11] N.A. Trayanova. Whole-heart modeling: Applications to cardiac electrophysiology and electromechanics. *Circ.*
23 *Res.*, 108:113–128, 2011.
- 24 [12] P. Nardinocchi and L. Teresi. On the active response of soft living tissues. *J. Elasticity*, 88(1):27–39, 2007.
- 25 [13] C. Cherubini, S. Filippi, P. Nardinocchi, and L. Teresi. An electromechanical model of cardiac tissue: Constitutive
26 issues and electrophysiological effects. *Progr. Biophys. Molec. Biol.*, 97(23):562 – 573, 2008.
- 27 [14] D. Ambrosi, G. Arioli, F. Nobile, and A. Quarteroni. Electromechanical coupling in cardiac dynamics: the
28 active strain approach. *SIAM J. Appl. Math.*, 71(2):605–621, 2011.
- 29 [15] S. Rossi, T. Lassila, R. Ruiz-Baier, A. Sequeira, and A. Quarteroni. Thermodynamically consistent orthotropic
30 activation model capturing ventricular systolic wall thickening in cardiac electromechanics. *Eur. J. Mechanics*
31 *A/Solids*, 48:129–142, 2014.
- 32 [16] D. Ambrosi and S. Pezzuto. Active stress vs. active strain in mechanobiology: constitutive issues. *J. Elasticity*,
33 107(2):199–212, 2012.
- 34 [17] S. Rossi, R. Ruiz-Baier, L.F. Pavarino, and A. Quarteroni. Orthotropic active strain models for the numerical
35 simulation of cardiac biomechanics. *Int. J. Numer. Meth. Biomed. Engrg.*, 28:761–788, 2012.
- 36 [18] P.G. Ciarlet. *Mathematical Elasticity, Vol I : Three-Dimensional Elasticity*. North-Holland, Amsterdam, 1978.
- 37 [19] J.M. Ball. Convexity conditions and existence theorems in nonlinear elasticity. *Arch. Rational Mech. Anal.*,
38 63(4):337–403, 1976/77.
- 39 [20] P. Krejčí, J. Sainte-Marie, M. Sorine, and J.M. Urquiza. Solutions to muscle fiber equations and their long
40 time behaviour. *Nonl. Anal.: Real World Appl.*, 7(4):535 – 558, 2006.
- 41 [21] G.A. Holzapfel and R.W. Ogden. Constitutive modelling of passive myocardium: a structurally based frame-
42 work for material characterization. *Phil. Trans. Royal Soc. Lond. A*, 367:3445–3475, 2009.
- 43 [22] J. Sundnes, S. Wall, H. Osnes, T. Thorvaldsen, and A.D. McCulloch. Improved discretisation and linearisation
44 of active tension in strongly coupled cardiac electro-mechanics simulations. *Comput. Meth. Biomech. Biomed.*
45 *Engrg.*, 17(6):604–615, 2014.
- 46 [23] D. Baroli, A. Quarteroni, and R. Ruiz-Baier. Convergence of a stabilized discontinuous Galerkin method for
47 incompressible nonlinear elasticity. *Adv. Comput. Math.*, 39(2):425–443, 2013.
- 48 [24] D.A. Nordsletten, S.A. Niederer, M.P. Nash, P.J. Hunter, and N.P. Smith. Coupling multi-physics models to
49 cardiac mechanics. *Progr. Biophys. Molec. Biol.*, 104(13):77–88, 2011.
- 50 [25] P. Pathmanathan, S.J. Chapman, D.J. Gavaghan, and J.P. Whiteley. Cardiac electromechanics: the effect of
51 contraction model on the mathematical problem and accuracy of the numerical scheme. *Quart. J. Mech. Appl.*
52 *Math.*, 63(3):375–399, 2010.
- 53 [26] P. Pathmanathan, C. Ortner, and D. Kay. Existence of solutions of partially degenerate visco-elastic problems,
54 and applications to modelling muscular contraction and cardiac electro-mechanical activity. *Submitted*, 2013.
- 55 [27] Boris Andreianov, Mostafa Bendahmane, Alfio Quarteroni, and Ricardo Ruiz-Baier. Solvability analysis and
56 numerical approximation of linearized cardiac electromechanics. *Mathematical Models and Methods in Applied*
57 *Sciences*, 25(05):959–993, 2015.
- 58 [28] Go W Beeler and H Reuter. Reconstruction of the action potential of ventricular myocardial fibres. *The Journal*
59 *of physiology*, 268(1):177–210, 1977.
- 60 [29] Ching-hsing Luo and Yoram Rudy. A dynamic model of the cardiac ventricular action potential. i. simulations
61 of ionic currents and concentration changes. *Circulation research*, 74(6):1071–1096, 1994.
- 62 [30] F. Nobile, A. Quarteroni, and R. Ruiz-Baier. An active strain electromechanical model for cardiac tissue. *Int.*
63 *J. Numer. Meth. Biomed. Engrg.*, 28:52–71, 2012.

- 1 [31] J. Sundnes, G.T. Lines, X. Cai, B.F. Nielsen, K.-A. Mardal, and A. Tveito. *Computing the electrical activity in*
2 *the heart*, volume 1 of *Monographs in Computational Science and Engineering*. Springer-Verlag, Berlin, 2006.
- 3 [32] D.M. Bers. Cardiac excitation-contraction coupling. *Nature*, 415(6868):198–205, 2002.
- 4 [33] R. Ruiz-Baier, A. Gizzi, S. Rossi, C. Cherubini, A. Laadhari, S. Filippi, and A. Quarteroni. Mathematical
5 modeling of active contraction in isolated cardiomyocytes. *Math. Medicine Biol.*, 31:259–283, 2014.
- 6 [34] R. Ruiz-Baier, D. Ambrosi, S. Pezzuto, S. Rossi, and A. Quarteroni. Activation models for the numerical
7 simulation of cardiac electromechanical interactions. In G.A. Holzapfel and E. Kuhl, editors, *Computer Models*
8 *in Biomechanics: From nano to macro*, pages 189–201. Springer-Verlag, Heidelberg, 2013.
- 9 [35] A. Laadhari, R. Ruiz-Baier, and A. Quarteroni. Fully Eulerian finite element approximation of a fluid-structure
10 interaction problem in cardiac cells. *Int. J. Numer. Methods Engrg.*, 96(11):712–738, 2013.
- 11 [36] Pierre-Arnaud Raviart, Jean-Marie Thomas, Philippe G Ciarlet, and Jacques Louis Lions. *Introduction à*
12 *l'analyse numérique des équations aux dérivées partielles*, volume 2. Dunod Paris, 1998.
- 13 [37] J.-L. Lions. *Quelques méthodes de résolution des problèmes aux limites non linéaires*. Dunod; Gauthier-Villars,
14 Paris, 1969.
- 15 [38] H.W. Alt and S. Luckhaus. Quasilinear elliptic-parabolic differential equations. *Mathematische Zeitschrift*,
16 183:311–342, 1983.
- 17 [39] Lawrence C. Evans. *Partial Differential Equations*, volume 19 of *Graduate Studies in Mathematics*. American
18 Mathematical Society, Providence, Rhode Island, 1998.
- 19 [40] Franck Boyer and Pierre Fabrie. *Mathematical tools for the study of the incompressible Navier-Stokes equations*
20 *and related models*, volume 183. Springer Science & Business Media, 2012.
- 21 [41] Jean Bourgain and Haïm Brezis. On the equation $\operatorname{div} v = f$ and application to control of phases. *Journal of the*
22 *american mathematical society*, 16(2):393–426, 2003.
- 23 [42] Douglas N Arnold, L Ridgway Scott, and Michael Vogelius. Regular inversion of the divergence operator with
24 dirichlet boundary conditions on a polygon. 1987.
- 25 [43] Georges de Rham. Differentiable manifolds, volume 266 of *grundlehren der mathematischen wissenschaften*.
26 *Berlin: Springer*, 1(9):84, 1984.
- 27 [44] Xiaoming Wang. A remark on the characterization of the gradient of a distribution. *Applicable Analysis*,
28 51(1-4):35–40, 1993.
- 29 [45] Jacques Simon. Démonstration constructive dun théorème de g. de rham. *CR Acad. Sci. Paris Sér. I Math*,
30 316(11):1167–1172, 1993.
- 31 [46] Roger Temam. *Navier-Stokes equations: theory and numerical analysis*, volume 343. American Mathematical
32 Soc., 2001.
- 33 [47] Jindrich Nečas. Sur les normes équivalentes dans $w_p^k(\omega)$ et sur la coercivité des formes formellement positives.
34 *Les presses de l'Université de Montréal*, 1966.
- 35 [48] Jindrich Nečas. *Direct methods in the theory of elliptic equations*. Springer Science & Business Media, 2011.

36 (Mostafa Bendahmane)

37 INSTITUT DE MATHÉMATIQUES DE BORDEAUX (IMB) ET L'INSTITUT DE RYTHMOLOGIE ET MODÉLISATION CARDIAQUE
38 (LIRYC), UNIVERSITÉ DE BORDEAUX ET INRIA-CARMEN BORDEAUX SUD-OUEST

39 *E-mail address*: mostafab@math.uio.no

40 *URL*: <http://math.uio.no/~mostafab/>

41 (Fatima Mroue)

42 LABORATOIRE DE MATHÉMATIQUES, ECOLE DOCTORALE DES SCIENCES ET TECHNOLOGIES, UNIVERSITÉ LIBANAISE,
43 HADAT, DÉPARTEMENT DE MATHÉMATIQUES, CENTRALE NANTES

44 *E-mail address*: fatima.mroue@ec-nantes.fr

45 (Mazen Saad)

46 DÉPARTEMENT DE MATHÉMATIQUES, CENTRALE NANTES AND LABORATOIRE DE MATHÉMATIQUES JEAN LERAY

47 *E-mail address*: mazen.saad@ec-nantes.fr

48 (Raafat Talhouk)

49 LABORATOIRE DE MATHÉMATIQUES, ECOLE DOCTORALE DES SCIENCES ET TECHNOLOGIES, UNIVERSITÉ LIBANAISE,
50 HADAT

51 *E-mail address*: rtalhouk@ul.edu.lb