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Modeling the heart, cell by cell

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In nearly all cardiac diseases, abnormal tissue structure plays an important if not crucial role. Reduced mechanical and electrical coupling between myocytes and death of individual cells can increase local functional heterogeneity and lead to arrhythmogenic situations on a very small scale. Faithful numerical simulations of these phenomena require models in which individual cells and inter-cellular connections are discretized. Yet, nearly all current models are based on homogenization approaches with spatial scales that are much larger than a single cell.

Until now, homogenization has been necessary to make whole-heart simulations possible. Even today, discretizing each of the two billion myocytes in the human heart, let alone its nearly ten billion other cells, is not feasible. But with supercomputers approaching exaFLOP speeds (10^{18} floating-point operations per second) and memory sizes in the order of petabytes, cell-by-cell simulations of a mouse heart or a human atrium seem reachable. Still, a huge effort and a wide variety of expertise is needed to achieve the roughly 200,000-fold scale increase that this involves and to build model geometries representing millions of cells with billions of elements.

In the EuroHPC project MICROCARD we have tackled every aspect of this challenge. We have developed numerical schemes, linear solvers, and preconditioners that are tailored to the problem and to the high level of parallelization that is required [3,4]; we increased the performance of cardiac membrane models on high-performance architectures [5]; we developed tissue models both using imaging data and using fully synthetic methods [6]; and we are working on a simulation code that brings all these pieces together.

In this presentation I will illustrate the rationale for this work and highlight the project's achievements, some of which are already available to the community through improvements in the openCARP code, the Ginkgo linear algebra library, and the Mmg remeshing tools.

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