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Electrocardiology modeling after pulsed field ablation relying on asymptotic analysis

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In healthy hearts, the propagation of electrical waves follows a predictable pattern, whereas in people suffering from arrhythmia, the electrical waves can become chaotic and directly affect the pumping function of the heart. One of the main treatments for these arrhythmias is catheter ablation, which destroys small areas of heart tissue to isolate or eliminate the cause of the rapid and irregular heartbeats. Most catheter ablation therapies are performed thermally through the application of a radiofrequency electromagnetic field (RFA). Some limitations and disadvantages are observed in clinical application, such as damage to adjacent structures.
In this work, we focus on the study of a novel and mainly non-thermal ablation technique: pulsed electric field ablation (PFA), which takes advantage of irreversible electroporation, a complex phenomenon of cell membrane rupture that occurs when biological tissue is exposed to very intense electric pulses. This technique has been used in oncology for more than a decade, but it is still in its infancy in cardiology. Preclinical evaluations of PFA in atrial fibrillation and ventricular ablation in large animal studies show successful results with possible transmural lesions. Despite these promising results, the application of PFA in routine clinical practice still presents some difficulties because of the technical complexity of this novel approach. Mathematical models and numerical strategies could be developed to improve the understanding of PFA on the cardiac signal and to develop numerical criteria for treatment assessment based on clinical data. The aim of this work is to derive a cardiac electrophysiological model of a cardiac domain containing a region ablated by PFA. In doing so, we start from the following three points: (1) the electroporated region is small compared with the entire domain, (2) the intra-cellular conductivity within the electroporated zone is also very small, and (3) a linearization of the ionic current is assumed in the electroporated region. The last two assumptions can be explained by the fact that the ablated tissue contains few cells and the gap junctions connecting the cells are severely compromised. This leads to a model that depends on a small parameter which could lead to numerical problems. To address this, an asymptotic analysis is performed in a static context and convergence analysis is explored. The strategy allows to determine the transmission conditions at the interface between the two regions, yielding a suitable model of a cardiac domain containing an ablation region by PFA. Well-designed Schwarz algorithms are developed to numerically solve the obtained PDE system.

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