Electromechanical modeling of cardiac arrhythmias

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1. INTRODUCTION

Cardiac arrhythmias arise from an abnormality in the rhythm of the human heart. Among them, ventricular tachycardia (VT), which manifests with a fast heart rate, is one of the most life threatening rhythm disorders. VT may be classified as hemodynamically stable or unstable, depending on the capability of the heart to effectively pump blood in the circulatory system. In the former case antiarrhythmic drugs are generally employed, while in the latter case cardioversion is needed. According to the specific pathogenesis, the stability of the VT remains the same or changes over time. Moreover, it may also degenerate towards ventricular fibrillation (VF), a life-threatening condition in which the ventricular activity is fully disorganized and chaotic, leading to heart failure.

In the clinical framework, these pathological scenarios can be hardly ever fully investigated and predicted for all patients. For this reason, biophysically detailed computational heart models could be used to provide a deeper understanding of the hemodynamic response to VT and to characterize the electromechanical substrate leading to dangerous arrhythmias.

Electrophysiological simulations are well-established for scar-related VT identification and treatment on human ventricles (Arevalo et al. (2016); Prakosa et al. (2018)). On the contrary, patient-specific electromechanical models coupled with closed-loop cardiovascular circulation have been just recently used to enhance our knowledge on VT (Salvador et al. (2021)). Indeed, the physiological processes that couple mechanical and electrical activity of the human heart, known as mechano-electric feedbacks (MEFs), are relevant and not fully elucidated (Kohl et al. (2013); Colli Franzone et al. (2017); Keldermann et al. (2010)). Moreover, the identification of the hemodynamic nature of the VT has significant clinical implications.

In this study we analyze the impact of different modeling choices for the left ventricle (LV) myocardial deformation and the recruitment of nonselective stretch-activated channels (SACs) by combining electrophysiology, mechanics and hemodynamics in several numerical simulations. Furthermore, we also show that our computational model reproduces both hemodynamically stable and hemodynamically unstable VT.

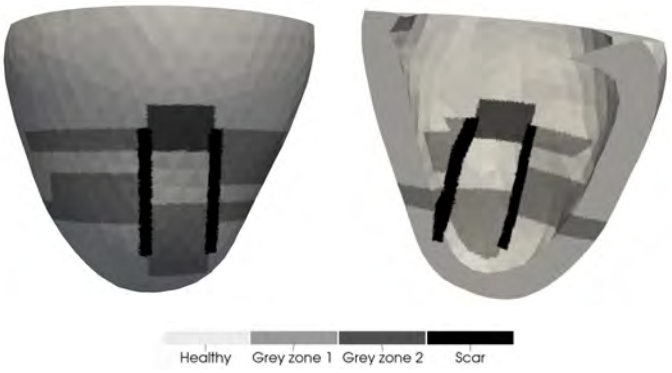

Fig. 1. Zygote LV with an idealized distribution of scars, grey zones and non-remodeled regions over the myocardium.

2. MATHEMATICAL MODELS AND METHODS

We consider the LV processed from the Zygote 3D heart model endowed with a fiber architecture generated by means of the Bayer-Blake-Plank-Trayanova algorithm and an idealized distribution of ischemic regions (Fig. 1). For cardiac electrophysiology, we employ the monodomain equation coupled with the ten Tusscher-Panfilov ionic model. In particular, we consider the monodomain equation with several degrees of complexity in MEFs mathematical modeling to assess similarities and differences in the outcomes of the numerical simulations during VT. We use a biophysically detailed and anatomically accurate active stress model to describe the active force generation mechanisms. The passive mechanical behavior of the myocardium is modeled through the Guccione constitutive law. We consider the interaction with the pericardium by means of spring-damper boundary conditions at the epicardium of the LV, while we prescribe energy-consistent boundary conditions at the base of the LV to model the interaction with the part of the heart beyond the artificial ventricular base. Regarding blood circulation, we rely on a 0D closed-loop model, consisting of a compartmental description of the cardiac chambers, systemic and pulmonary, arterial and venous circulatory networks, based on an electrical analogy. The different compartments are modeled as RLC (resistance, inductance, capacitance) circuits, while cardiac valves are described as diodes (Regazzoni et al. (2022)).

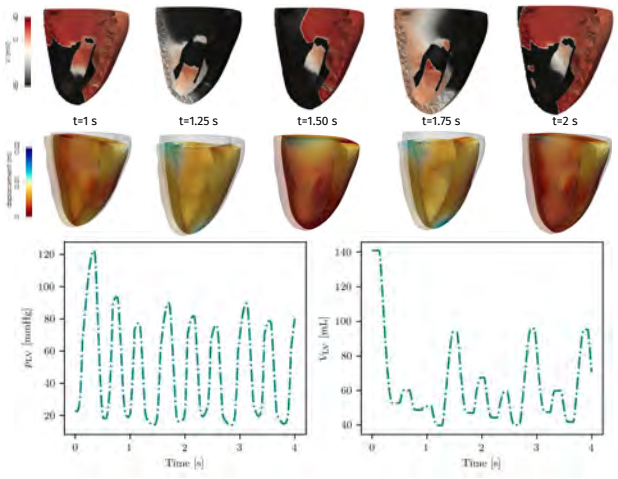

Fig. 2. Coupled effects of electrophysiology, mechanics and hemodynamics for a numerical simulation with geometric MEFs and SACs. The extra stimuli in the upper right part of the LV, which is driven by SACs, activate the LV electrophysiologically and mechanically. This has a direct impact on both pressure and volume transients, which in turn have an effect on the electromechanical behavior of the LV.

We adopt a segregated-intergrid-staggered scheme to numerically discretize this 3D-0D coupled problem (Regazzoni et al. (2022)). Indeed, the core models are solved sequentially by employing different space and time resolutions according to the specific requirements of electrophysiology, activation and mechanics.

3. DISCUSSION

We studied the effects of geometric and physiological MEFs on a realistic LV geometry endowed with an idealized distribution of infarct and peri-infarct zones. We performed numerical simulations of cardiac electromechanics coupled with closed-loop cardiovascular circulation under VT (Fig. 2).

First, we saw that if a VT is triggered by a certain stimulation protocol and by neglecting all MEFs, the very same pacing protocol induces a VT for all possible combinations of MEFs that we considered. Moreover, our electromechanical framework allows for the hemodynamic classification of the VT, which can be either stable or unstable, and permits to capture mechanically relevant indications under VT, such as the incomplete relaxation of sarcomeres.

With respect to electrophysiological simulations, we observed several differences on the morphology of the VT by combining electrophysiology, activation, mechanics and hemodynamics. In particular, geometric MEFs do not affect wave stability and may alter the VT basis cycle length, along with its exit site. On the other hand, the recruitment of SACs may generate extra stimuli, which may change wave stability. These extra stimuli are driven by myocardial contraction and are induced by changes in the action potential duration or its resting value. We conclude that both geometric and physiological MEFs define important contributions in electromechanical models, especially when numerical simulations under arrhythmia are carried out.

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