CARDIOSENSE3D : PATIENT-SPECIFIC CARDIAC SIMULATION

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ABSTRACT

In this paper, we overview the objectives and achievements of the CardioSense3D project dedicated to the construction of an electro-mechanical model of the heart.

***Index Terms*—** Cardiac Imaging, cardiac modeling, electrophysiology, electromechanical models, computational cardiac models

1. TOWARD QUANTITATIVE AND PERSONALIZED MEDICINE

There is an irreversible evolution of medical practice toward more quantitative and personalized decision procedures for prevention, diagnosis and therapy, based on ever larger and more complex sets of measurements. This deep trend induces a crucial need for producing a new type of so-called computational models of the anatomy and the physiology of the human body [1], able to explain the observations, detect abnormalities, predict evolutions, as well as to simulate and evaluate therapies. The simulation of the heart has received a growing attention due to the importance [2, 3, 4, 5, 6, 7] of cardiovascular diseases in industrialized nations[1] and to the high complexity of the cardiac function. Indeed, formulating a computational model of the cardiac function of a specific patient represents a great challenge due to :

- i) the intrinsic physiological complexity of the underlying phenomena which combine tissue mechanics, fluid dynamics, electro-physiology, energetic metabolism and cardiovascular regulation;
- ii) the partial information available for a specific patient and the variety of the objectives of data processing ranging from global detection of pathological situations to local diagnosis and personalized therapy planning.

[1] With 180 000 deaths per year, cardiovascular diseases represent the leading cause of death in France before cancer. In the United States more than 1 million deaths occur every year caused by cardio-vascular diseases.

2. CARDIOSENSE3D

CardioSense3D is a 4-year Large Initiative Action launched in 2005 and funded by the French national research center INRIA which focuses on the electro-mechanical modeling of the heart.

The **objectives** of **CardioSense3D** are threefold :

1. To **build a cardiac simulator**, with identifiable parameters, that couples 4 different physiological phenomena: electrophysiology, mechanical contraction and relaxation, myocardium perfusion and cardiac metabolism,
2. To **build data assimilation software** that can estimate patient specific parameters and state variables from given observations of the cardiac activity,
3. To **build several application softwares** based on this simulator and data assimilation techniques to solve clinical problems related to the diagnosis or therapy of cardiac pathologies.

in order to :

- **significantly improve medical practice** in terms of better prevention, diagnosis, quantitative follow-up, simulation and guidance of therapy,
- **support biomedical research** in the preparation and evaluation of new diagnostic and therapeutic tools,
- **advance** the **fundamental knowledge** of the integrative *physiology* of the **heart**.

CardioSense3D relies on the expertise of four INRIA research teams (resp. Asclepios, Reo, Macs, Sosso2) covering the fields of medical image analysis, computational structural

and fluid dynamics, numerical analysis and control. But is also a collaborative framework that involves clinical centers such as the Guy"s Hospital London, the Laboratory of Cardio-Energetics at the National Institutes of Health, the Hospital Henri Mondor (J. Garot), and other partners listed in the web site of the project[2].

Reaching those three objectives requires to tackle the following challenges :

1. The introduction of models and related numerical procedures to represent some important physiological phenomena still not considered, in particular: cardiac metabolism, perfusion and tissue remodeling. The extended models must remain identifiable with the available data and computationally tractable. This sets the limits of the otherwise endless quest for model fidelity and simulation accuracy.

2. The formulation of effective data assimilation methodologies associated with those models, that can estimate patient-specific indicators from actual measurements of the cardiac activity. Major shortcomings of existing methods include robustness and computational cost (the "curse of dimensionality").

3. The adaptation and optimization of the cardiac simulator (including both direct and inverse approaches) to some targeted clinical applications. For each application, specific problems connected with clinical science will be considered.

3. SOME CARDIOSENSE3D RESEARCH ACTIVITIES

We illustrate below some of recent research advances performed within CardioSense3D.

Statistical Analysis of Diffusion Tensor Imaging of canine hearts

In Figure 1 and 2, we show some recent results [8] concerning the statistical analysis of Diffusion Tensor Imaging (DTI) of nine canine hearts. Diffusion imaging helps to reveal the fine structure of the myocardium such as the fiber orientation and possibly the location and orientation of laminar sheets. This structural information is crucial for modeling both the mechanical and electrophysiological function of the heart.

Electro-physiology Modeling

Several electrophysiological models have been proposed within CardioSense3D, including front propagation techniques [9], phenomenological models [10] and a 8-variable cardiac cell model describing the dynamics of calcium [11]. Model-based

[2]www.inria.fr/CardioSense3D/

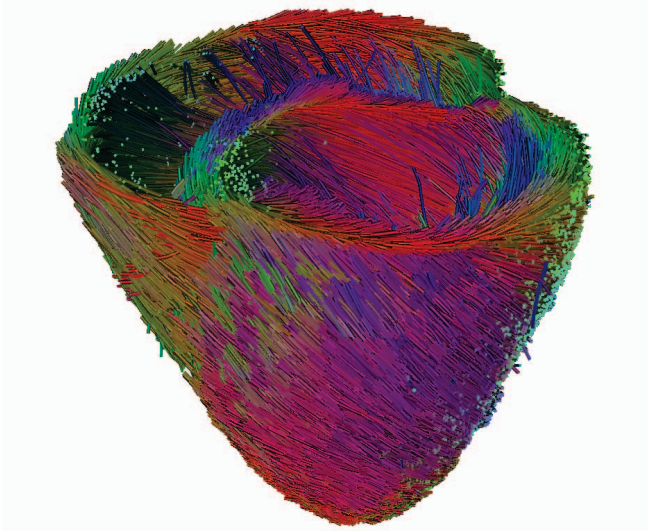


Fig. 1. Fiber tracking performed on an average Canine heart build from nine canine images.

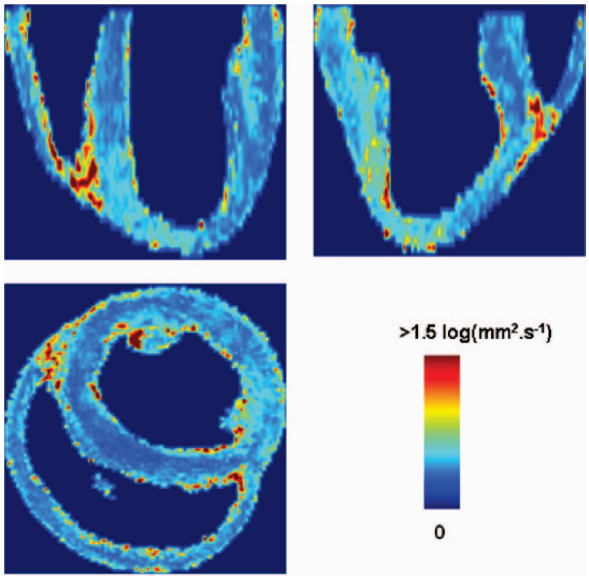


Fig. 2. Images of the trace of the covariance matrix of diffusion tensors from nine canine hearts. The variability of those tensors seems to be low in most part of the myocardium.

ECG processing for identification of restitution curves have also been proposed in [12].

Electro-mechanical model of the heart

The coupling between electrophysiology and mechanics [14] is governed by a chemically-controlled constitutive law which is consistent with general thermodynamics and with the be-

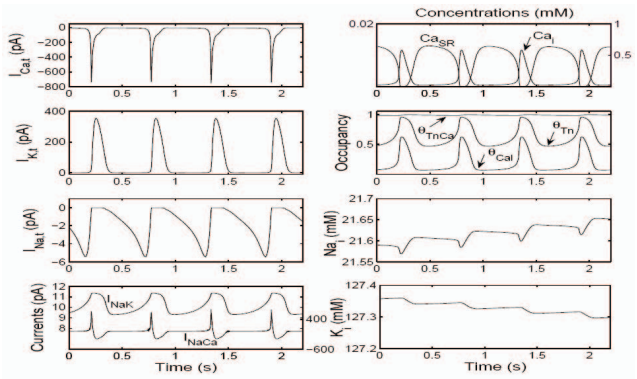
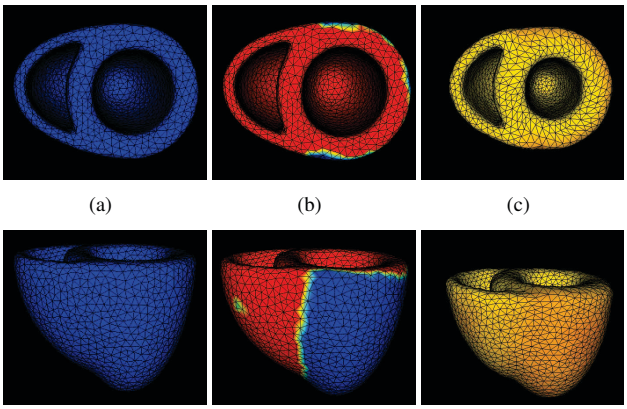


Fig. 3. Computed spontaneous action potential and ionic currents (left) and intracellular Ca^{++} dynamics (from [13]).

havior of myosin molecular motors. The biomechanical model is based on a Hill-Maxwell rheological scheme [15], pressure boundary conditions being controlled by valve and Winkessel models [16, 17]. Figure 4 shows the biventricular model at end diastole and end systole [17].



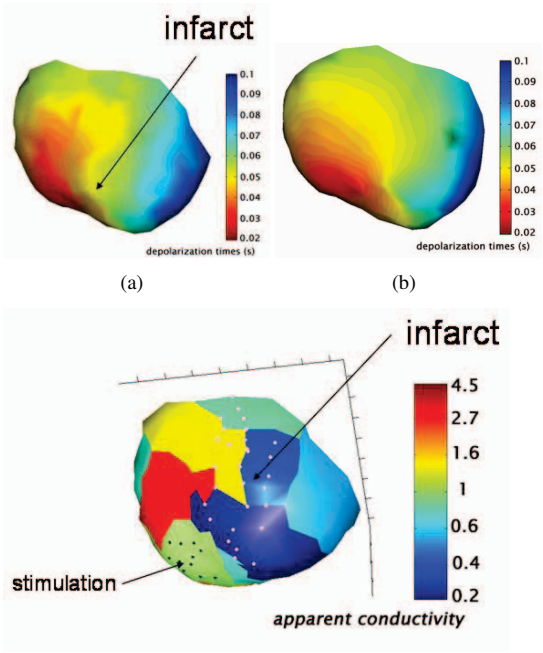
(a) (b) (c)

(d) (e) (f)

Fig. 4. Short axis (top row) and long axis (bottom row) views of an electromechanical heart model during end diastole (left column), ventricular depolarization (middle column) and end systole (right column).

Coupling Models with Observations

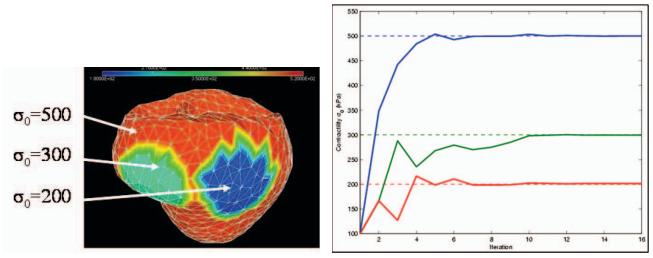
The objective of estimating model parameters from observations is a key aspect of CardioSense3D. Preliminary results have been obtained on this front, by globally integrating the electromechanical heart models with clinical datasets [18, 19] (3D endocardial mapping with tagged, SSFP and late enhancement MR images), by estimating apparent electrical conductivities from electrophysiological mappings [20] (see Figure 5) and by estimating regional contractilities [21, 16] from motion information (see Figure 6).



(a) (b)

(c)

Fig. 5. (a) Measured depolarization isochrones of a canine heart with an infarcted region; (b) Simulated depolarization isochrones based on a phenomelogical model after the automatic estimation of regional appearent conductivities; (c) View of the apparent conductivity map where regions of low conductivities matches infarcted regions.



(a) (b)

Fig. 6. (a) Three regions of an electro-mechanical model of the heart have been set with different contractility parameters; (b) A data assimilation technique has been used to recover those parameters.

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