Published in final edited form as:

IEEE Rev Biomed Eng. 2009 November 17; 2: 12. doi:10.1109/RBME.2009.2034695.

In the Spotlight: Cardiovascular Engineering

Natalia Trayanova

Department of Biomedical Engineering, The Johns Hopkins University, Baltimore, MD 21224 USA

Natalia Trayanova: ntrayanova@jhu.edu

The year in review marks the beginning of a new trend in cardiovascular engineering, the development of patient-specific image-based models of the heart and the circulatory system. The goal of this type of models is to provide better assessment of cardiovascular function under the patient-specific pathophysiological conditions and to serve as a testbed for improved cardiovascular therapies that are tailored to the patient. These new models constitute a part of the growing trend towards the development of new computational approaches (i.e., computational medicine) that can aid treatment and prevention of human disease.

In the paper by Jolley *et al.* [1] entitled “A computer modeling tool for comparing novel ICD electrode orientations in children and adults”, the authors use patient-specific, image-based finite element models of the human torso to compare electric field distributions in the torso for various electrode configurations, both standard and novel. The motivation of the study was that although implantable cardiac defibrillators (ICDs) have become the standard of care for patients at risk of fatal cardiac arrhythmias and are routinely implanted in adult patients using a transvenous approach, there is a growing population of pediatric and adult patients in whom transvenous ICD systems cannot or should not be implanted. These include patients of very small size and those with intracardiac shunts or anatomical obstructions to lead placement. In these patient populations, a variety of innovative approaches to ICD implantation must be developed, including subcutaneous, epicardial, and caval electrode placements and/or abdominal can implants. Using *ad hoc* adaptations of existing ICD components, current clinical approaches to ICD implantations in these patient groups attempt to minimize system invasiveness while incorporating patient-specific anatomical considerations. In the study by Jolley *et al.*, the authors modeled a spectrum of standard and unconventional ICD electrode orientations in torso models of various sizes, using an interactive electrode placement and modeling environment. Models were constructed by segmenting 64-detector computed tomography scans of subjects. Custom modular software allowed the user to insert coil and can electrodes into images of the segmented volume with anatomical precision. The intention of this approach was not to predict DFTs in a quantitative manner, but rather to explore trends and to provide relative comparisons of electrode performance. The principal finding of this study was that many of the surgical decisions made before and during ICD implantation in a given patient often result in large variations in the predicted efficiency of the system. The results suggested that prediction of efficient defibrillation strategies using interactive, image-based models is feasible and may be used to optimize ICD electrode placement in specific patients with nonstandard anatomy, to develop alternatives to standard transvenous techniques, and to test innovative ideas for the design of new devices.

Interventional and surgical therapies for atrial fibrillation (AF) have been targeting the isolation of the pulmonary veins, currently seen as the most reliable method in preventing episodes of paroxysmal AF. In recent years, various left atrial lesion patterns have been used in clinical practice. Numerous issues, however, remain to be resolved in order to improve and optimize ablation strategies, including those of lesion transmural and the use of linear vs. circumferential lesions. The paper of Reumann *et al.* [2] used a computer model of the atria to test different ablation lesion patterns in a single patient anatomical data set. The anatomical

model chosen for this study was the segmented atria from the visible female data set of the National Library of Medicine that additionally included wall thickness and detailed anatomical structures such as the crista terminalis, the pectinate muscles, and the Bachmann's bundle, achieving a degree of anatomical detail superior to previous atrial modeling efforts. AF was initiated in the model (using a complex cellular automata approach) and ten different left atrial ablation lesion sets were created in accordance with clinical approaches. Simulations demonstrated that circumferential lesions around the pulmonary veins yield the highest success rate if at least two additional linear lesions are also carried out. Furthermore, the specific anatomy of the atria and the distribution of ectopic beats played an important role in the success of the ablation strategy. The computer model presented in this paper could be a valuable approach to investigate different ablation strategies. By including individual patient anatomy and electrophysiological measurement, the model could be parameterized to become an effective tool in tailoring patient-specific ablation strategies.

Similarly to realistic torso and organ models of electric fields and cardiac electrophysiology, computational fluid dynamics (CFD) modeling of blood flow from image-based patient specific models can provide useful information for guiding clinical decision making. The paper by Shadden and Taylor [3] presented a novel method for the generation of three-dimensional image-based, multiscale vascular surface models for CFD. As the authors stated, the method was particularly useful for CFD modeling of complex vascular geometries that have a wide range of vasculature size scales. This paper is a part of a larger effort to couple, in a new manner, the separate advances in vascular biology, medical imaging, and computational biofluid and biosolid mechanics, creating a new class of computational tools, fluid-solid-growth models. The goal of this effort is to better understand the mechanobiology, pathophysiology, and treatment of a variety of aortic aneurysms, such as for instance intracranial saccular and abdominal, which continue to be responsible for significant morbidity and mortality in the patient population.

In another important development in cardiovascular engineering, a couple of recent studies [4], [5] present the first applications of electrocardiographic imaging (ECGI), a novel noninvasive imaging modality for the diagnosis and guided therapy of cardiac arrhythmias. ECGI combines multi-electrode body surface ECG recordings with three-dimensional anatomical heart-torso imaging (typically CT scans) to reconstruct an epicardial electroanatomic map. ECGI images can be presented as epicardial potential maps, electrograms, isochrones (activation sequences), or repolarization patterns during activation and repolarization of the heart. ECGI is currently being used to study mechanisms of various cardiac arrhythmias in patients and to guide therapeutic interventions. The study by Ghosh *et al.* [4] described a case where ECGI was applied to a pediatric patient with a congenital structural heart defect. The patient was a 12-year old female diagnosed at birth with tricuspid and pulmonary atresia and interrupted inferior vena cava with azygous continuation to the superior vena cava. Her 12-lead ECG showed persistent preexcitation consistent with Wolff-Parkinson-White syndrome. ECGI was used to localize the accessory pathway and guide intracardiac mapping during her electrophysiologic procedure. While the 12-lead ECG-based Arruda algorithm predicted a right lateral pathway, ECGI potential and activation maps showed pre-excitation in the anteroseptal area below the aortic valve annulus. This case study demonstrated the feasibility of ECGI in patients with congenital heart disease and engendered the promise of further application of the ECGI technology for understanding the underlying electrophysiology in similar cases. In [5], fourteen pediatric patients with Wolff-Parkinson-White syndrome and no other congenital disease were imaged with ECGI a day before and 45 minutes, 1 week, and 1 month after successful catheter ablation. The study demonstrated that ECGI could noninvasively localize ventricular insertion sites of accessory pathways to guide ablation and to evaluate its outcome in pediatric patients with Wolff-Parkinson-White syndrome. These are very important advancements in noninvasive imaging of for diagnosis

and guided therapy of cardiac arrhythmias, and the application of this novel technique is expected to quickly grow in the near future.

During the year in review, significant advances were made in the use of biophysically detailed models of cardiac electrical activity to understand the mechanisms by which arrhythmias arise and are maintained in the heart. An example is the study by Kildermann *et al.* [6], which aimed to investigate the effect of heterogeneous restitution properties in a realistic three-dimensional model of the human ventricles. The model, a first of its kind, incorporated detailed descriptions of cell electrophysiology, human ventricular anatomy, and fiber direction anisotropy, as well as clinically measured restitution properties. The clinical restitution properties, as measured in cardiac patients, included a substantial degree of heterogeneity in restitution slopes. The study examined the effects of restitution heterogeneity on the organization of ventricular fibrillation (VF) by analyzing the scroll-wave filaments and the distributions of excitation periods. The number of filaments and the excitation periods were found to depend on the extent of the restitution heterogeneity. Thus, restitution heterogeneity was found to play an important role in arrhythmogenesis by providing a substrate for cardiac arrhythmias. This study exemplifies a new trend: to use species-specific cardiac geometry and electrophysiology to understand the specific conditions under which arrhythmia are formed and sustained in the heart.

Finally, a novel analysis of defibrillation mechanisms was achieved using another biophysically detailed model, this time of the rabbit ventricles. The paper by Ashihara *et al.* [7] proposed a new theory of shock-induced arrhythmogenesis that unifies many known aspects of the response of the heart to monophasic and biphasic shocks. The central hypothesis of the paper was that submerged “tunnel” propagation of post-shock activations through shock-induced intramural excitable areas underlies VF induction and the existence of isoelectric window. The results of the simulations demonstrated that during the isoelectric window, activations originated deep within the ventricular wall, arising from virtual electrodes; they then propagated fully intramurally through an excitable tunnel induced by the shock, until they emerged onto the epicardium, becoming the earliest-propagated postshock activation. This study provided a novel analysis of the 3D mechanisms underlying the origin of postshock activations in the process of VF induction by monophasic and biphasic shocks and the existence of isoelectric window. The tunnel propagation hypothesis is an important novel concept that could open a new avenue for the exploration of alternative approaches to achieve significantly lower defibrillation thresholds.

It has been an exciting year for cardiovascular engineering.

References

1. Jolley M, Stinstra J, Pieper S, Macleod R, Brooks DH, Cecchin F, Triedman JK. A computer modeling tool for comparing novel ICD electrode orientations in children and adults. *Heart Rhythm* 2008;5:565–72. [PubMed: 18362024]
2. Reumann M, Bohnert J, Seemann G, Osswald B, Dössel O. Preventive ablation strategies in a biophysical model of atrial fibrillation based on realistic anatomical data. *IEEE Trans Biomed Eng* Feb;2008 55(2 pt 1):399–406. [PubMed: 18269975]
3. Shadden SC, Taylor CA. Characterization of coherent structures in the cardiovascular system. *Ann Biomed Eng* 2008;36:1152–62. [PubMed: 18437573]
4. Ghosh S, Avari JN, Rhee EK, Woodard PK, Rudy Y. Non-invasive Electrocardiographic Imaging (ECGI) of epicardial activation before and after catheter ablation of the accessory pathway in a patient with Ebstein anomaly. *Heart Rhythm* 2008;5:857–860. [PubMed: 18482872]
5. Ghosh S, Rhee EK, Avari JN, Woodard PK, Rudy Y. Cardiac memory in patients with Wolff-Parkinson-white syndrome: Noninvasive imaging of activation and repolarization before and after catheter ablation. *Circulation* 2008;118:907–915. [PubMed: 18697818]

6. Keldermann RH, ten Tusscher KH, Nash MP, Hren R, Taggart P, Panfilov AV. Effect of heterogeneous APD restitution on VF organization in a model of the human ventricles. *Am J Physiol Heart Circ Physiol* 2008;294:H764–74. [PubMed: 18055526]
7. Ashihara T, Constantino J, Trayanova NA. Tunnel propagation of postshock activations as a hypothesis for fibrillation induction and isoelectric window. *Circ Res* 2008;28(102):737–45. [PubMed: 18218982]