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Medical Image Analysis – Special Issue FIMH 2023

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Editorial

Medical Image Analysis – Special Issue FIMH 2023

Editorial

The 12th edition of the international Functional Imaging and Modeling of the Heart (FIMH, <https://fimh2023.sciencesconf.org/>) conference was held in Lyon, France, on June 19-22 2023. FIMH is a biennial scientific event that aims to integrate state-of-the-art research and novel development efforts in the fields of cardiovascular imaging, image analysis, and heart modeling, both from the methodological and clinical sides. With over 130 registered participants, 20 oral presentations and 52 posters published in the Lecture Notes in Computer Science (LNCS – FIMH-23, volume 13958, Springer) (<https://link.springer.com/book/10.1007/978-3-031-35302-4>), this edition was an exciting return to Lyon 20 years after the second edition of the conference in 2003. The program also featured 3 associated workshops and 1 data challenge.

This special issue of the Medical Image Analysis journal introduces 5 papers that were collectively selected among the presentations during the conference by the scientific and organizing committees.

Romitti et al., introduce a Cellular Automaton (CA) model tailored to replicate atrial electrophysiology in different stages of Atrial Fibrillation (AF), including persistent AF. Their CA model allowed a significant decrease in computing time compared to the biophysical solver while presenting very promising performance in predicting AF inducibility.

Banduc et al. propose a classification method to predict AF inducibility in patient-specific cardiac models without additional simulations. The approach introduces the fibrotic kernel signature, a set of features faster to compute than a single AF simulation, which, when paired with machine learning classifiers, can predict AF inducibility in the entire domain within clinical timelines.

Still on the AF management, Qureshi et al. leverage patient-specific MRI-based computational fluid dynamic modeling of left atrial flow coupled with kinetics equations for blood constituent clotting proteins, leading to an innovative risk stratification score for thrombus formation in AF patients.

Khaledian et al. propose a subject-specific fluid–structure simulation framework based on the immersed boundary method to produce accurate simulations of mitral valve closure and maps of contact reflecting the quality of the closure. They extracted valve geometries from 3D CT data of porcine hearts, and investigated both isotropic and anisotropic valve models. The latter were shown to represent the physiological characteristics of the valve tissue more accurately.

Finally, in the context of congenitally corrected transposition of the great arteries (ccTGA), and its treatment through a double switch operation (DSO), Gusseva et al. propose a computational modeling framework to reconstruct left (LV) and right-ventricular (RV) pressure-volume loops and gather model-derived mechanical indicators of

ventricular function; and to perform in silico DSO to predict the functional response of the LV when connected to the high-pressure systemic circulation. This in-silico DSO approach was experimented on 6 pre-trained patients, 3 of whom were identified as requiring a substantial augmentation of the contractility to accommodate the increased after-load of the systemic circulation.

This paper selection is a nice illustration of high-quality works presented at FIMH, and of current developments mixing clinical data, advanced computer modeling and data analysis approaches for cardiovascular applications. We really much look forward to new contributions to the field at the next FIMH conference on June 2025 in Dallas.

Patrick Clarysse,
Nicolas Duchateau,
Olivier Bernard,
Jacques Ohayon,
Magalie Viallon
FIMH 2023 organization committee,
Guest editors

Papers

Romitti et al.,
Implementation of a Cellular Automaton for efficient simulations of atrial arrhythmias

Abstract

In silico models offer a promising advancement for studying cardiac arrhythmias and their clinical implications. However, existing detailed mathematical models often suffer from prolonged computational time compared to diagnostic needs. This study introduces a Cellular Automaton (CA) model tailored to replicate atrial electrophysiology in different stages of Atrial Fibrillation (AF), including persistent AF (PsAF).

The CA, using a finite set of states, has been trained using biophysical simulations on a reduced domain for a large set of pacing conditions. Fine-tuning included tissue heterogeneity and anisotropic propagation through pacing simulations. Characterized by Action Potential Duration (APD), Diastolic Interval (DI) and Conduction Velocity (CV) for varying levels of electrical remodeling, the biophysical simulations introduced restitution curves or surfaces into the CA. Validation involved a comprehensive comparison with realistic 2D and 3D atrial models, evaluating healthy and pro-arrhythmic behaviors. Comparisons between CA and biophysical solver revealed striking proximity, with a Cycle Length difference of <10 ms in self-sustained re-entry and a 4.6+0.57 ms difference in depolarization times across the complete atrial geometry. Notably, the CA model exhibited a 80% accuracy, 96% specificity and 45% sensitivity in predicting AF inducibility under

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different pacing sites and substrate conditions. Additionally, the CA allowed for a 64-fold decrease in computing time compared to the biophysical solver.

CA emerges as an efficient and valid model for simulation of atrial electrophysiology across different stages of AF, with potential as a general screening tool for rapid tests. While biophysical tests are recommended for investigating specific mechanisms, CA proves valuable in clinical applications for personalized therapy planning through digital twin simulations.

Highlights

- Considering restitution properties, Cellular Automata replicate atrial biophysical results.
- Cellular Automata reduce computational demands for AF simulations in clinical time.
- By reducing computational time, Cellular Automata enable exploring arrhythmic scenarios.

Keywords

Atrial arrhythmias, Cellular Automata, Computational models
Banduc et al.,

Simulation-free prediction of atrial fibrillation inducibility with the fibrotic kernel signature

Abstract

Computational models of atrial fibrillation (AF) can help improve success rates of interventions, such as ablation. However, evaluating the efficacy of different treatments requires performing multiple costly simulations by pacing at different points and checking whether AF has been induced or not, hindering the clinical application of these models. In this work, we propose a classification method that can predict AF inducibility in patient-specific cardiac models without running additional simulations. Our methodology does not require re-training when changing atrial anatomy or fibrotic patterns. To achieve this, we develop a set of features given by a variant of the heat kernel signature that incorporates fibrotic pattern information and fiber orientations: the fibrotic kernel signature (FKS). The FKS is faster to compute than a single AF simulation, and when paired with machine learning classifiers, it can predict AF inducibility in the entire domain. To learn the relationship between the FKS and AF inducibility, we performed 2371 AF simulations comprising 6 different anatomies and various fibrotic patterns, which we split into training and a testing set. We obtain a median F1 score of 85.2% in test set and we can predict the overall inducibility with a mean absolute error of 2.76 percent points, which is lower than alternative methods. We think our method can significantly speed-up the calculations of AF inducibility, which is crucial to optimize therapies for AF within clinical timelines. An example of the FKS for an open source model is provided in https://github.com/tbanduc/FKS_AtrialModel_Ferrer.git.

Highlights

- We introduce a novel machine learning classifier to predict atrial fibrillation.
- The classifier includes all the information about the anatomy and fibrosis.
- We can predict atrial fibrillation inducibility without running simulations.
- The method opens the door for fast personalization of therapies.

Keywords

Heat kernel signature, Machine learning, Atrial fibrillation, Fibrosis, Patient-specific modeling
Qureshi et al.,

MRI-based modelling of left atrial flow and coagulation to predict risk of thrombogenesis in atrial fibrillation

Abstract

Atrial fibrillation (AF), impacting nearly 50 million individuals globally, is a major contributor to ischaemic strokes, predominantly originating from the left atrial appendage (LAA). Current clinical scores like CHA₂DS₂-VASc, while useful, provide limited insight into the pro-thrombotic mechanisms of Virchow's triad—blood stasis, endothelial damage, and hypercoagulability. This study leverages biophysical computational modelling to deepen our understanding of thrombogenesis in AF patients. Utilising high temporal resolution Cine magnetic resonance imaging (MRI), a 3D patient-specific modelling pipeline for simulating patient-specific flow in the left atrium was developed. This computational fluid dynamics (CFD) approach was coupled with reaction-diffusion-convection equations for key clotting proteins, leading to an innovative risk stratification score that combines clinical and modelling data. This approach categorises thrombotic risk into low (A), moderate (B), and high (C) levels. Applied to a cohort of nine patients, pre- and post-catheter ablation therapy, this approach generates novel risk scores of thrombus formation, which are based of mechanistic characterisation of all aspects of the Virchow's triad. Currently, thrombogenesis mechanisms are not factored in widespread clinical risks scores based on demographic characteristics and co-morbidities. Notably, some patients with a CHA₂DS₂-VASc score of 0 (lowest clinical risk) exhibited much higher risks once the individual pathophysiology was accounted for. This discrepancy highlights the limitations of the CHA₂DS₂-VASc score in providing detailed mechanistic insights into patient-specific thrombotic risk. This work introduces a comprehensive method for assessing thrombus formation risks in AF patients, emphasising the value of integrating biophysical modelling with clinical scores to enhance personalised stroke prevention strategies.

Highlights

- Novel MRI-based framework for modelling atrial flows coupled with blood coagulation facilitates patient-specific quantification of thrombogenesis.
- Patients imaged during AF showed higher risks of thrombus formation in the left atrial appendage due to altered flow conditions and blood constituents compared to sinus rhythm.
- Mechanistic prediction of Virchow's triad - blood stasis, hypercoagulability, and endothelial damage - can help to overcome the limitations of current clinical risk stratification scores.

Keywords

Atrial fibrillation, Stroke, Digital twin, Left atrial appendage, Medical imaging, Virchow's triad, Thrombus formation, CFD

Khaledian et al.,

Image-based simulation of mitral valve dynamic closure including anisotropy

Abstract

Simulation of the dynamic behavior of mitral valve closure could improve clinical treatment by predicting surgical procedures outcome. We propose here a method to achieve this goal by using the immersed boundary method. In order to go towards patient-based simulation, we tailor our method to be adapted to a valve extracted from medical image data. It includes investigating segmentation process, smoothness of geometry, case setup and the shape of the left ventricle. We also study the influence of leaflet tissue anisotropy on the quality of the valve closure by comparing with an isotropic model. As part of the anisotropy analysis, we study the influence of the principal material direction by comparing methods to obtain them without dissection.

Results show that our method can be scaled to various image-based data. We evaluate the mitral valve closure quality based on measuring bulging area, contact map, and flow rate. The results show also that the anisotropic material model more precisely represents the physiological characteristics of the valve tissue. Furthermore, results indicate that the orientation of the principal material direction plays a role in the effectiveness of the valve seal.

Highlights

- The main contribution is to prove the scalability of our method to any medical-based data.
- We extended the literature review on the material models used for modeling the mitral valve behavior.
- We discussed the challenges in obtaining material parameters for the constitutive law.
- We investigate the influence of surface smoothness from the segmentation process on the simulation results.
- We investigate the difference between using a fitted tube and a large cylinder to represent the left ventricle.

Keywords

Fluid–structure interaction, Mitral valve, Constitutive model, Fiber model, Immersed boundary, Segmentation

Gusseva et al.,

Biomechanical modeling combined with pressure-volume loop analysis to aid surgical planning in patients with complex congenital heart disease

Abstract

Patients with congenitally corrected transposition of the great arteries (ccTGA) can be treated with a double switch operation (DSO) to restore the normal anatomical connection of the left ventricle (LV) to the systemic circulation and the right ventricle (RV) to the pulmonary circulation. The subpulmonary LV progressively deconditions over time due to its connection to the low pressure pulmonary circulation and needs to be retrained using a surgical pulmonary artery band (PAB) for 6–12 months prior to the DSO. The subsequent clinical follow-up, consisting of invasive cardiac pressure and non-invasive imaging data, evaluates LV preparedness for the DSO. Evaluation using standard clinical techniques has led to unacceptable LV failure rates of ~15 % after DSO. We propose a computational modeling framework to (1) reconstruct LV and RV pressure-volume (PV) loops from non-simultaneously acquired imaging and pressure data and gather model-derived mechanical indicators of ventricular function; and (2) perform in silico DSO to predict the functional response of the LV when connected to the high-pressure systemic circulation.

Clinical datasets of six patients with ccTGA after PAB, consisting of cardiac magnetic resonance imaging (MRI) and right and left heart

catheterization, were used to build patient-specific models of LV and RV – $M_{baseline}^{LV}$ and $M_{baseline}^{RV}$. For in silico DSO the models of $M_{baseline}^{LV}$ and $M_{baseline}^{RV}$ were used while imposing the afterload of systemic and pulmonary circulations, respectively. Model-derived contractility and Pressure-Volume Area (PVA) – i.e., the sum of stroke work and potential energy – were computed for both ventricles at baseline and after in silico DSO.

In silico DSO suggests that three patients would require a substantial augmentation of LV contractility between 54 % and 80 % and an increase in PVA between 38 % and 79 % with respect to the baseline values to accommodate the increased afterload of the systemic circulation. On the contrary, the baseline functional state of the remaining three patients is predicted to be adequate to sustain cardiac output after the DSO.

This work demonstrates the vast variation of LV function among patients with ccTGA and emphasizes the importance of a biventricular approach to assess patients' readiness for DSO. Model-derived predictions have the potential to provide additional insights into planning of complex surgical interventions.

Highlights

- Analysis of image and pressure data by patient-specific biophysical modeling.
- Biventricular assessment for patients with complex congenital heart disease.
- Model predicts the effect of pulmonary artery banding on subpulmonary left ventricle.
- Model allows to assess the preparedness for high-risk cardiac surgery.
- Model-derived prediction contributes to the optimization of treatment strategies.

Keywords

Cardiac magnetic resonance imaging, Pressure-volume loops, Biomechanical modeling, Complex congenital heart disease

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.