

# Computer-assisted Planning of Cardiac Interventions and Heart Surgery

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**Abstract:** Medical imaging techniques like Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) are able to deliver high-resolution 3D images of the human heart. New acquisition techniques even allow measuring 4D images: 3D plus time. They show the details of the contraction of the heart. Multichannel Electrocardiography (ECG) can be used to measure relevant characteristics of the electrophysiology of the heart. In parallel, new methods have made their way into the "catheter laboratory" to measure electrophysiological data from inside the heart using localizable, multichannel catheter electrodes. In summary, a huge amount of data is acquired to support the cardiologist and the heart surgeon - the problem is to merge all the information to a clear diagnostic picture. Mathematical models simulate the electrophysiology and the elastomechanics of the heart with a very high degree of precision. This article presents first results on the way to merge all the measured data (MRI, CT, ECG, catheter-electrodes) to a "virtual heart of the patient" in order to support the physician during diagnosis and therapy planning..

## 1 Introduction

In the context of the "Physiome Project" [HU06] mathematical models of the heart have been developed over the past decade that are now able to reconstruct the main features of electrophysiology and elastomechanics of the healthy human heart. Some of the most important diseases like infarction, atrial flutter and fibrillation, ventricular flutter and fibrillation, branch-block, etc. are basically understood. The models demonstrate their possibilities using generalized models or the geometry of the visible human dataset - no link to an individual patient is made until now. This way, these models serve for basic research to understand the underlying mechanisms of heart function and diseases and they help to ask the right questions for further research. They can also be used for learning and training in cardiology.

The diagnostic methods in cardiology have reached a very high level during the last decade. One of the most important features is the acquisition of end diastolic 3D data sets using MRI or CT. These imaging data allow e.g. for the segmentation and quantification of ventricular volumes, detection of stenosis in the coronary arteries and evaluation of tissue viability after myocardial infarction. They also allow to determine complete 3D maps of the coronary artery tree as well as the coronary sinus for planning of interventions and navigation. With new methods of MRI and CT even 4D images can be acquired, that allow for a visualization of the contraction pattern of a patients heart.

Classical ECG (Einthoven or Wilson leads) can be expanded to the measurement of complete maps of the electric potentials across the thoracic surface called Body Surface Potential Maps (BSPM). In addition, electrical signals are acquired from inside the heart using catheter. In some systems the tip of the catheter can be localized using magnetic fields (Carto, Biosense). In other systems 64-channel catheters are expanded inside the heart (Balloon, Ensite Solutions or Basket, Boston Scientific). They deliver continuously the electric potentials inside the heart at 64 positions simultaneously and are able to detect details of genesis and perpetuation of various arrhythmias. Today, out of the large amount of measured electrophysiological data, the cardiologist has to construct a picture of the pathology of the patient in his/her mind. This picture leads him/her to one out of a set of therapeutic options starting from pharmacological treatment or RF-ablation and ending with the implantation of a pacemaker. Unfortunately the success rate of many of these antiarrhythmic measures is not very high. Our hypothesis is, that the picture in the mind of the cardiologist is not always sufficiently near to the reality of the problem of the patient.

In heart surgery we observe an increase in interventions to reconstruct the shape of the left ventricle over the last years. One reason can be an aneurysm that has to be removed; another reason might be a strong dilatation of the heart after many years of heart failure that leads to a very small stroke volume. The best way to carry out this type of heart surgery would be to improve the contraction and the stroke volume without destabilizing the electrophysiology of the heart. If the patient wakes up after surgery with a good pumping power of the heart but dies after some months from ventricular fibrillation the first success is lost again.

For all these open questions in cardiology and heart surgery, computer models of the heart offer the chance for substantial improvement of therapy planning. The aim is to use all the measured data (MRI, CT, ECG, BSPM, Intracardial Mapping) to set up a virtual heart of the individual patient. This virtual heart can be used for thorough therapy planning. All options can be tried out and the long-term consequences can be calculated, visualized and evaluated. Only after this individualized therapy planning the best option will be realized.

## 2 Computer Model of Electrophysiology of Myocardial Cells

Mathematical Models of the electrophysiological behaviour of myocardial cells start with sets of differential equations describing ion channels [NO02]. As an example, the Sodium ion channel consists of five gates and each gate can be modelled following the Hodgkin Huxley approach with a linear first order differential equation. The rate constants depend on the transmembrane voltage and can be measured using voltage clamp and/or patch clamp technique. The non-linear system of differential equations can only be solved numerically. In this article the Euler one step method is used with fixed step size. Many different ion channels are embedded into the cell membrane of a myocardial cell. There are many different types of myocardial cells with a different mixture of ion channels. Typically 20 differential equations are coupled to describe one cardiomyocyte. With properly chosen rate constants meanwhile the electrophysiological behaviour of myocardium cells are understood and described for all types of experiments nearly perfectly - theory and experiment fit in all circumstances.

Figure 1 shows as an example the time course of the transmembrane voltage of different tissue types in the human atria.

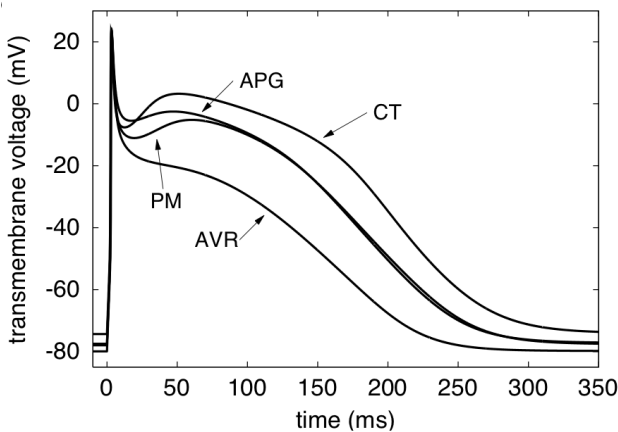


Figure 1: Time course of the transmembrane voltage of different tissue types in the human atria  
CT: crista terminalis, PM: pectinate muscles, APG: appendage, AVR: atrioventricular ring,  
[SE04].

## 3 Computer Model of Heart Tissue and the Complete Heart

In the heart, billions of cells are coupled both electrically and mechanically. The electrical coupling is described mathematically using the so-called bidomain model, leading to a Poisson type partial differential equation [HE96]. The intracellular and extracellular conductivities are anisotropic - they have to be described as tensors. Both Finite Element Method (FEM) and Finite Difference Method (FDM) are used to solve the Poisson equation. In this article FDM is used. At the same time the state variables of

a million symbolic myocardium cells have to be followed using the methods described above. Splitting the total volume of the heart into 22 segments the algorithm can be translated to parallel processing on 22 processors speeding up calculation time significantly. In this article an Apple G5 cluster is used with 2\*11 processors (IBM power PC G5, 2\*2GHz). LAM/MPI is used for parallelization [LAM]. Finally a complete atrial or ventricular model can be constructed starting from a given heart geometry and the precise segmentation of all tissue types with given electrophysiological properties. Figure 2 shows as an example some snapshots of the spread of depolarisation in the human left ventricle [WE05].

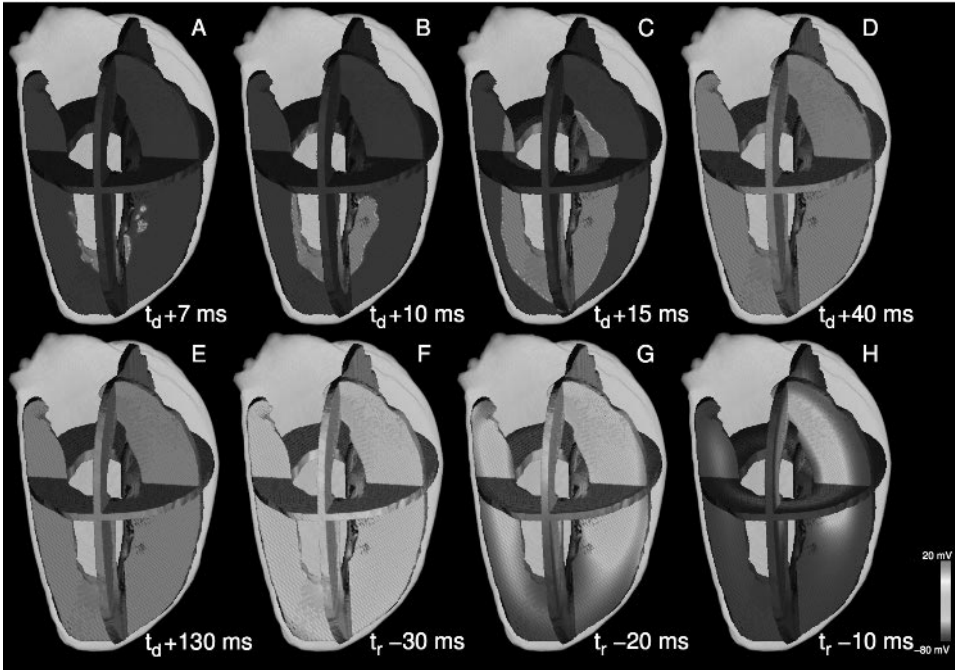


Figure 2: Spread of depolarisation in the human left ventricle [WE05]

#### 4 Modelling the Spread of Excitation using a Cellular Automaton

The calculation time for one heart beat (about 1s real time) in the left ventricle using the very detailed mathematical approach described above takes about 14 hours. For therapy planning this is much too long. For that reason a simplified version was implemented that uses the scheme of a cellular automaton. The slope of the transmembrane voltage of all relevant tissue types is stored in memory together with the velocity of the depolarization front. The cellular automaton used in this article is adaptive in the following sense: depending on the time that elapsed after the last depolarization different slopes of action potential are loaded from the memory. This way, also very early depolarisations like they can be observed during tachycardia, can be described properly.

With the cellular automaton a complete heart beat can be modelled in 4 min. Also, various pathologies like reduced conduction velocity, bundle branch block and infarction can be modelled. Figure 3 shows the spread of depolarization in the atria for the case of atrial fibrillation using a cellular automaton [RE05]. The cellular automaton was adapted to the anatomy of individual patient data after segmentation of 3D-MRI datasets.

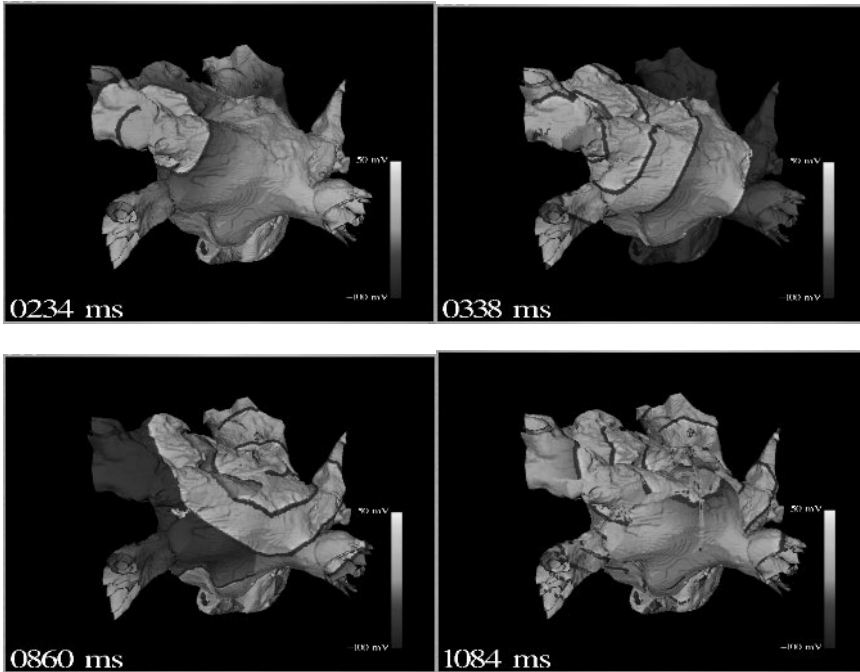


Figure 3: Spread of depolarization in the atria in case of atrial fibrillation calculated using a cellular automaton [RE05]

## 5 Computer Model of Electrocardiography ECG

Using the bidomain model the impressed current sources can be calculated: they follow the spatial gradient of the transmembrane voltage. These currents are used as the source term in a Poisson equation that describes the electric potential throughout the body. This way both the intracardial electric signals that are measured with catheter electrodes can be calculated and the electric potentials at the body surface (ECG and BSPM). Any change of parameters in the cellular automaton, e.g. for pathological cases can be observed in the ECG and the BSPM - and compared to the ECG and BSPM of real patients [FA04]. The models presented in this article lead to ECG signals that resemble the really observed data to a large degree, but sometimes significant differences are observed that have to be investigated further. Figure 4 shows the case of an infarcted heart. The "forward calculated" ECG shows clearly the elevation of the ST-segment like in real patients. All this was carried out using the geometry of an individual patient.

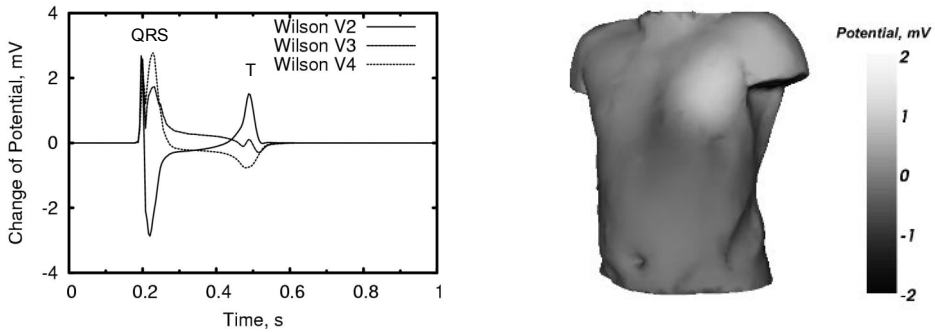


Figure 4: ECG and BSPM (at 332ms) of a simulated patient with infarction Q

## 6 Computer Model of Elastomechanics of Cells and Tissue

The contraction of the myocardium cells follows the electrical depolarization in a way that has been measured in detail in various laboratories worldwide. It is known, that the release of Calcium triggers the tension development. A cascade of processes inside the cells and in the myosin actin system takes place, that can be described by coupled differential equations. Knowing the tension in the individual cells the deformation of the tissue can be calculated employing the passive elastic properties of myocardial tissue. These passive properties are by far not trivial: they are anisotropic and non-linear. The tissue of the heart is sucked with blood and therefore incompressible. In this work the elastic deformation of the tissue was calculated using a hybrid spring mass model. Linear springs in conjunction with the energy density function of Guccione [GU91] were used to model the mechanical behaviour. The incompressibility is included using a hyperelastic material description of Mooney Rivlin. Figure 5 shows the simulated contraction of a left human ventricle. It can be compared with the 4D data from MRI or CT [MO06]. To our knowledge this is the first time that a simulation of the contraction of an individual human heart of a living patient was realized.

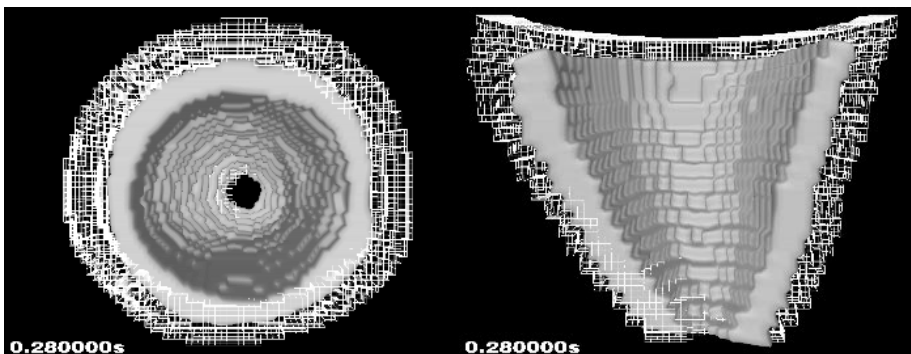


Figure 5: Simulated contraction of the human left ventricle [MO06]

## 7 Example of Therapy Planning: Optimization of Ablation

As an example of the possibilities of computer modelling of the heart a virtual ablation procedure was modelled and evaluated. RF-Ablation is a wide spread therapy for atrial fibrillation. Using a catheter that feeds RF-power into a spot inside the heart, the tissue is made necrotic. It cannot transmit the electrical depolarization any more, and specific paths of conduction are interrupted. Various schools of ablation strategies can be found worldwide; all do not have very high success rates up to now. Using a cellular automaton and ectopic centres in the pulmonaries typical patterns of atrial fibrillation can be created. Now, the various ablation strategies are evaluated and the success rate and the reasons for failure can be investigated. Figure 6 shows the simulation of the ablation strategy proposed by Benussi et al. [BE00].

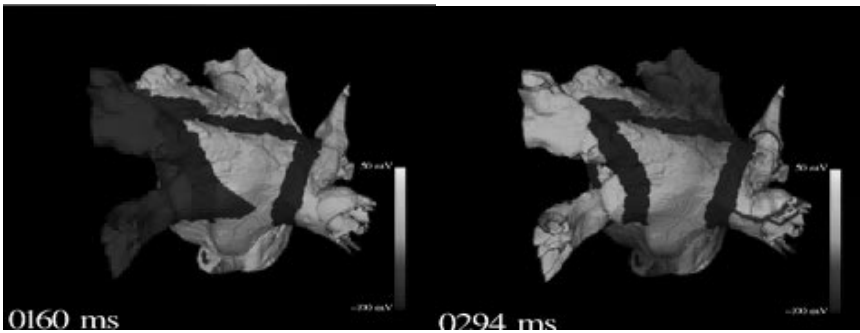


Figure 6: Ablation strategy of Benussi simulated using the cellular automaton [RE05]. The two pictures show the TMP at two different times of activation. The lines are virtual ablation lines.

## 8 Adaptation of the Standard Model to the Individual Patient - the Virtual Patient

Up to now only first and careful attempts have been made to adapt the computer model of the heart to the problem of an individual patient. First the geometry of the individual heart has to be taken from 3D MRI or CT data. Secondly using basic rules of physiology the fibre direction and the specific electrophysiological tissue types like the AV-node and the Purkinje fibres have to be included. Then a calculation of electrophysiology and contraction can be started using standard parameters of the heart. The comparison with the really measured MRI/CT and ECG will show significant differences, since we are dealing with a patient having a specific cardiac problem. In close cooperation with the cardiologist selected parameters of the computer model have to be modified in order to fit the simulation to the measured data.

If this process is successful a computer model of the individual patient - the "virtual heart of the patient" - has been finally realized. It can be used for all types of therapy planning starting from pharmacological approaches, RF-ablation or pacemaker and ending with the planning of complex surgical procedures.

## 9 Conclusions

This article shows up a new vision of computer-assisted therapy planning for cardiological interventions and heart surgery. Some of the steps have already been realized: A computer model of the physiological standard heart is operational including electrophysiology and elastomechanics. For some specific parts an iterative adaptation to individual patient data was successfully carried out. This already delivers further insight into the basic reasons of the pathology of a patient. A much more specific diagnosis is possible. The next step will be a systematic implementation and evaluation of some of the most important therapeutic measures in cardiology today.

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