2D Simulation of Cardiac Tissue

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Abstract: A two-dimensional atrial tissue model has been constructed to study the propagation of action potential and electrograms. The model presents the atrial electrograms recorded with a mapping catheter. The model can be stimulated to produce an action potential identical to human electrograms. The model is simulated using the Courtemanche et al. cell model equations. The electrical propagation of the cardiac impulse is obtained by solving a reaction diffusion system based on the ionic model. The model is capable of being modified to study the effect of recording electrode size and location on electrograms.

Keywords: Action Potential Propagation, Electrograms, Atrial Tissue, Atrial Fibrillation, Ablation

1. Introduction

Computational models of cardiac electrical activity and action potential propagation are becoming increasingly important for understanding the development and propagation mechanisms of arrhythmias and have received considerable attention.
During cardiac mapping, local atrial electrograms are recorded with a mapping catheter to analyze the electrical activity of the atrium. A small mapping catheter including some electrodes records the surface electrical activity of the atrium at different locations. It is then used to investigate the sites of triggers of arrhythmias.

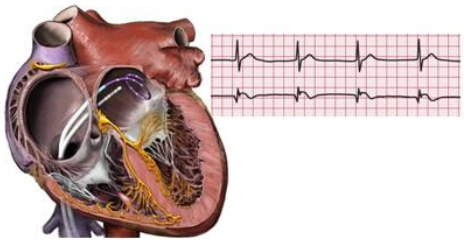

Figure 1 - Sinus rhythm recorded during mapping procedure.

This work presents a detailed numerical model of a two-dimensional slice of human atrial tissue using the complex Courtemanche, et al atrial cell model. In this work, the atrial electrograms is reproduced using COMSOL Multiphysics®, a finite element method (FEM) based simulation software.

2. Methods

A two-dimensional model of human atrial tissue was developed using an ionic-based membrane model. A small section of atrial tissue was constructed with one type of cell. The cells making up the tissue were assumed to be identical and connected to each other in a uniform way. The tissue was assumed to be isotropic; hence the conductivity tensors were set to a same value in two directions. There are no currents flowing into and out of the tissue.
Cardiac cells are connected to one another via gap junctions. The electric propagation of the cardiac impulse is described by a reaction-diffusion system assuming a monodomain, model given by: [1]

$$C_m \frac{\partial V_m}{\partial t} = S_v^{-1} \nabla . \sigma \nabla V_m + I_{st} - I_{ion} \qquad (1)$$

where V_m is the transmembrane voltage (mV), C_m=1(μF/cm^2) represents the membrane capacitance, S_v=0.24(μm^{-1}) the cell surface to volume ratio, σ the electrical conductivity tensor, I_{st} is the external stimulus current density to generate action potential and I_{ion} is the total ionic current calculated using the Courtemanche cell model. [2]

In the Courtemanche et al. model, the total ionic current is given by:

$$I_{ion} = I_{Na} + I_{K1} + I_{to} + I_{Kur} + I_{Kr} + I_{Ks} + I_{Ca,L} + I_{p,Ca} + I_{NaK} + I_{NaCa} + I_{b,Na} + I_{b,Ca} \qquad (2)$$

The ionic current is a function of transmembrane potential, gating and ion concentration, total of 21 nonlinear differential equations.

The extracellular potential Φ_e was modeled based on a current source approximation for a large unbounded volume conductor: [3]

$$\Phi e\ (x, y, t) = \frac{1}{4\pi\sigma_e} \sum \frac{I_m}{|r|} \qquad (3)$$

where σ_e is the extracellular conductivity (the saline bath conductivity) 1.5 (S/m), |r| is the distance between the recording electrode and the tissue, and I_m is the transmemrane current ($\mu A/cm^3$) given by:

$$I_m = \nabla \cdot \sigma \nabla V_m \qquad (4)$$

The unipolar electrograms were modeled relative to the zero reference potential in an unbounded bath. Bipolar atrial electrograms are more distinct and therefore more reliable. Bipolar electrograms was also modeled by taking the difference between the two unipolar electrograms. The unipolar electrograms were compared to the unipolar recording of a patient electrograms. The effect of electrode size and position on the shape of the signal was analyzed using the constructed model.

3. Use of COMSOL Multiphysics

In COMSOL Multiphysics®, PDE in coefficient form was used to implement Equ. 1:

$$e_a \frac{\partial^2 V}{\partial t^2} + d_a \frac{\partial V}{\partial t} + \nabla(-c\nabla V - \alpha V + \gamma) + aV + \beta\nabla V = f \qquad (5)$$

The ionic current (I_{ion}) is taken from the cell model. 21 nonlinear differential equations solved in Matlab and linked to COMSOL.

For the two-dimensional tissue simulation, we considered a simplified model with an assumption that the cells behave the same. A rectangular stimulus impulse was applied to the electrode and the action potential propagation is calculated in the domain. Figure 2 shows the membrane action potential as a function of time at 4 different locations.

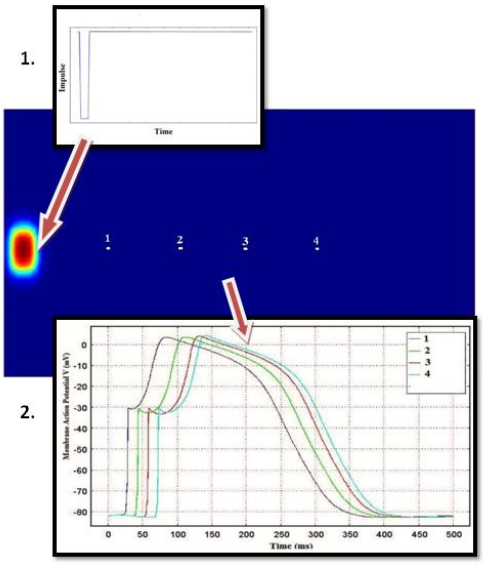

Figure 2 - Membrane action potential V as a function of time at 4 different locations. Stimulation impulse (1). Action potential propagation in the tissue (2).

The extracellular potential on the tissue is calculated using the transmembrane current I_m Equ. 4 reproduced using another PDE in coefficient form in COMSOL Multiphysics®.

An electrode array similar to the mapping catheter used in human recording is introduced to the model to calculate the extracellular potential on the tissue.

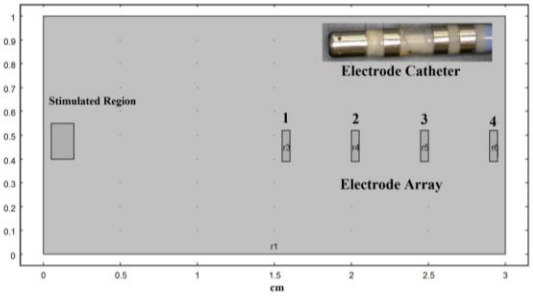

Figure 3 - 2D tissue model with electrode arrays to model atrial electrograms.

The electrograms were reproduced by implementing extracellular potential Φ_e, Equ. 3 in COMSOL. Figure 4 shows a comparison between the model and human atrial electrograms.

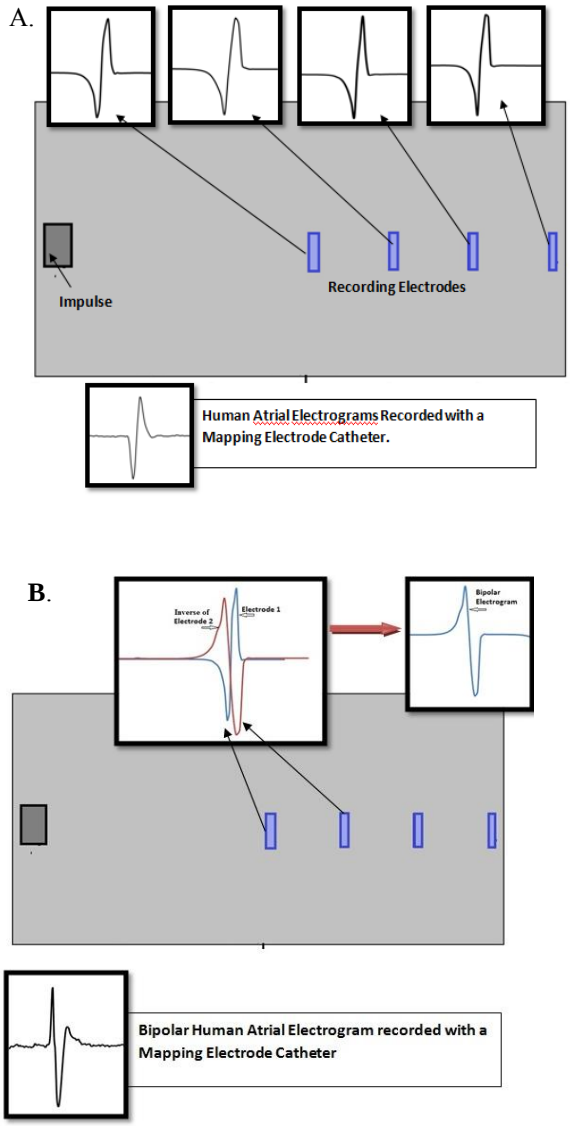

Figure 4 - A. Unipolar atrial electrograms. B. Bipolar atrial electrograms.

The model was used to study the effect of recording electrode size and location on electrograms. The size of the electrode is a significant factor in reducing the background noise during the electrogram recording. The area of the electrode plates is proportional to the signal to noise ratio. Therefore, the smaller the surface area of the plate is, the less background noise will capture. Figure 5 shows unipolar electrograms computed from the electrode 1 in the model. It shows that the signal to noise ratio increases by increasing the electrode surface area by factors of 2 and 4. A1 is the electrode surface area.

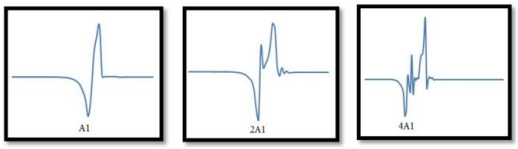

Figure 5 - Unipolar electrograms modeled using different electrode surface area.

Another important factor in electrogram recording using electrode array is the distance between the recording electrode and the tissue. It is proportional to the amplitude size of the signal. An increase in the distance of the recording electrode and the tissue decreases the amplitude of the signal. Typical distance between the recording electrode and tissue during mapping procedure is approximately 5mm. Figure 6 represents that increasing the distance between the recording electrode and tissue decreases the amplitude of the signal.

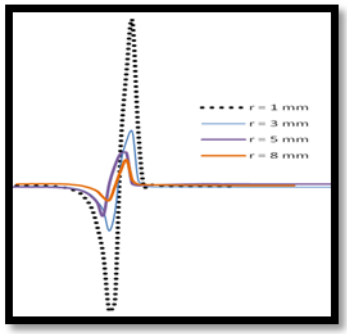

Figure 6 - Unipolar electrogram computed in 4 different distances.

7. Conclusions

Using COMSOL Multiphysics® PDE in coefficient form, atrial action potential propagation and electrograms were reproduced. The results were in agreement with the human atrial electrograms recorded at right atrial sites in a patient. The model was used to study the effect of recording electrode size and location on electrograms during cardiac mapping procedure.

8. References

1. Henriquez, C. S., & Papazoglou, A. A., Using computer models to understand the roles of tissue structure and membrane dynamics in arrhythmogenesis . *Proc. IEEE , 84* (3), 334–354 (1996).
2. Courtemanche, M., Ramirez, R. J., & Nattek, S., Ionic mechanisms underlying human atrial action potential properties: insights from a mathematical model. *Am J Physiol Heart Circ Physiol , 275*, 301-321(1998).
3. Lesh, D. M., Spear, F. J., & Simson, B. M. A, Computer Model of the Electrogram. pp. 69-73(1988).