Computational Modeling of Electrocardiogram Signals

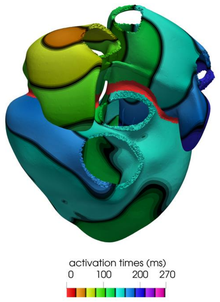
Preetam Tanikella

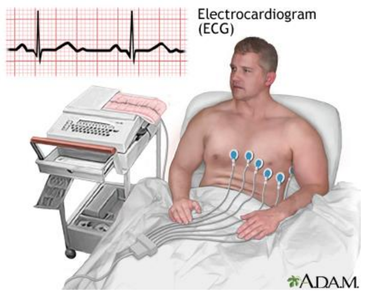
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

Background

Novel cardiac electrophysiology models are being developed to simulate the complex electrical systems of the heart. These models combine experimental data and mathematical algorithms to help researchers investigate normal cardiac rhythms, identify abnormalities, and create new therapeutic interventions for cardiac disorders.

ECGs are the primary clinical tool used to understand the heart's electrical activity. By calculating the electrocardiogram (ECG) traces for these cardiac electrophysiology models and comparing them to clinical data, we can improve the validity of these models and further our understanding of the relationship between heart function and ECG patterns used in clinical practice. One such method to compute ECG traces is the ϕ_e recovery method.





Extracellular Potential Recover Method

$$\phi_e = \frac{1}{4\pi\sigma_b}\int_{\Omega}\frac{\beta I_m}{||r||}d\Omega$$

Where σ_b is the conductivity tensor of the extracellular bath, β is the surface to volume ratio, r is the distance vector between the electrode and the source, and I_m is transmembrane currents.

$$I_m = C_m\left(\frac{\partial V_m}{\partial t}\right) + I_{ion}$$

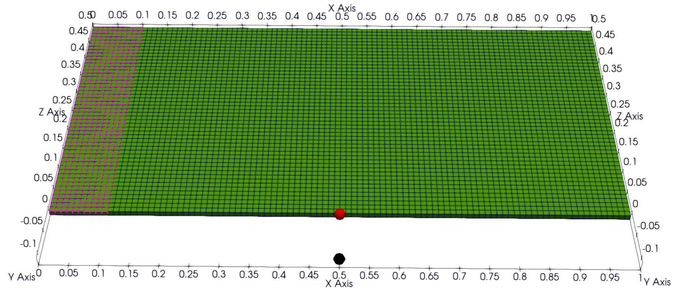
Where C_m is the membrane capacitance per unit area, V_m is the transmembrane voltage, and I_{ion} is the total membrane ionic current density.

The solution to the equation can be approximated through the finite element method and Euler's Method:

$$\phi_e = \frac{\beta}{4\pi\sigma_b}\Sigma_{DoFs}\frac{C_m * M\left[V_m^{n+1}(DoF) - V_m^n(DoF)/_{\Delta t}\right] + M[I_{ion}(DoF)]}{||r_{electrode} - r_{DoF}||}$$

Where M is the Mass Matrix and DoF is each degree of freedom.

Tissue Setup



- 1.0 x 0.01 x 0.5 cm (x, y, z) regular hexahedral finite element tissue with a total of 7000 elements and 14342 nodes

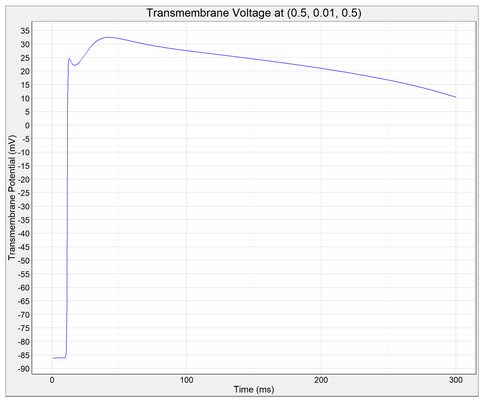
Conductivity Tensors

σ_l (fiber direction)	σ_t (cross-fiber direction)	σ_n (cross-fiber direction)	σ_b (extracellular bath)
0.574 mS/cm	0.222 mS/cm	0.222 mS/cm	10 mS/cm

(Siemens is 1/Ohm)

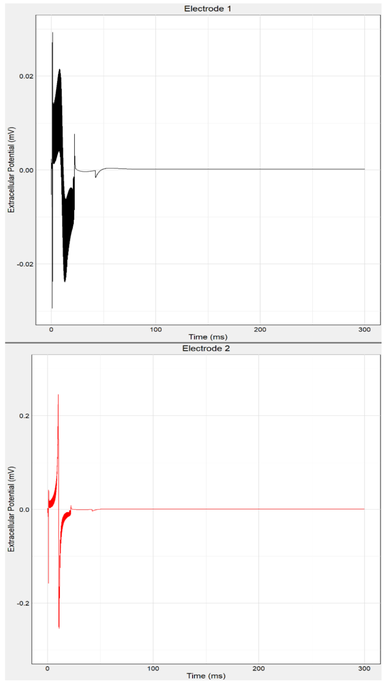
- The surface to volume ratio (β) was set at 1400 cm^{-1}
- The ionic model Ten Tusscher-Panfilov 2006 (TP06) model was used to represent the cell membrane dynamics within the myocardial tissue
- The tissue had a membrane capacitance of 1 $\frac{\mu F}{cm^2}$ and a resting potential of -86.2 mV
- The transmembrane voltage was computed by a monodomain model

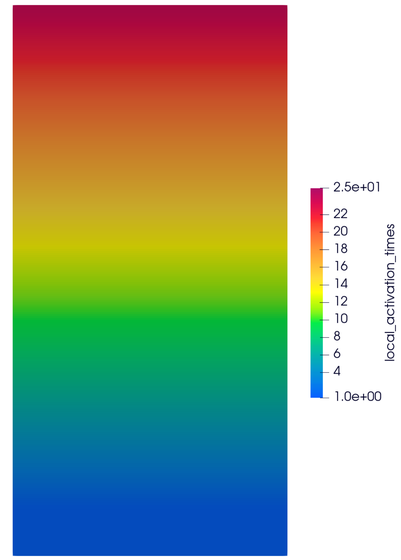
Stimulation Protocol



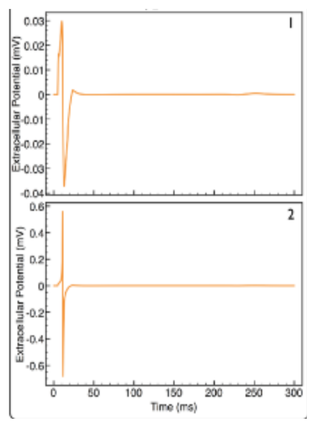
- A transmembrane current pule of 50 $\frac{\mu A}{cm^2}$ was applied to the slab over 1 ms along the volume of X ≤ 0.1 cm causing propagation along the x axis.
- The simulation took place over 300 ms with an ODE time-step of 5 μs

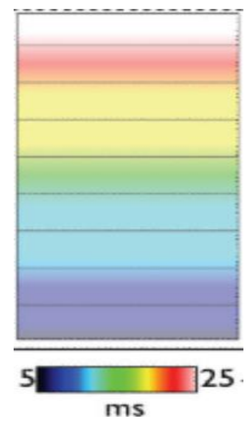
Results





- The maximum transmembrane voltage was 32.5 mV
- The tissue was completely activated by 25 ms
- The region around the electrode is activated around 10 ms corresponding to the spike in ϕ_e
- The shape of the ECG trace matches that from the Bishop simulation that ran similar protocol
- The activation maps for both simulations are the same
- Differences in ϕ_e amplitude are due to different ionic models and pacing amplitudes





References

Bishop M. J., Plank G. (2011a). Bidomain ECG Simulations Using an Augmented Monodomain Model for the Cardiac Source. *IEEE Trans. Biomed. Eng.* 58, 2297–2307. 10.1109/TBME.2011.2148718 Reference two