Effect of a Plunge Electrode During Field Stimulation of Cardiac Tissue

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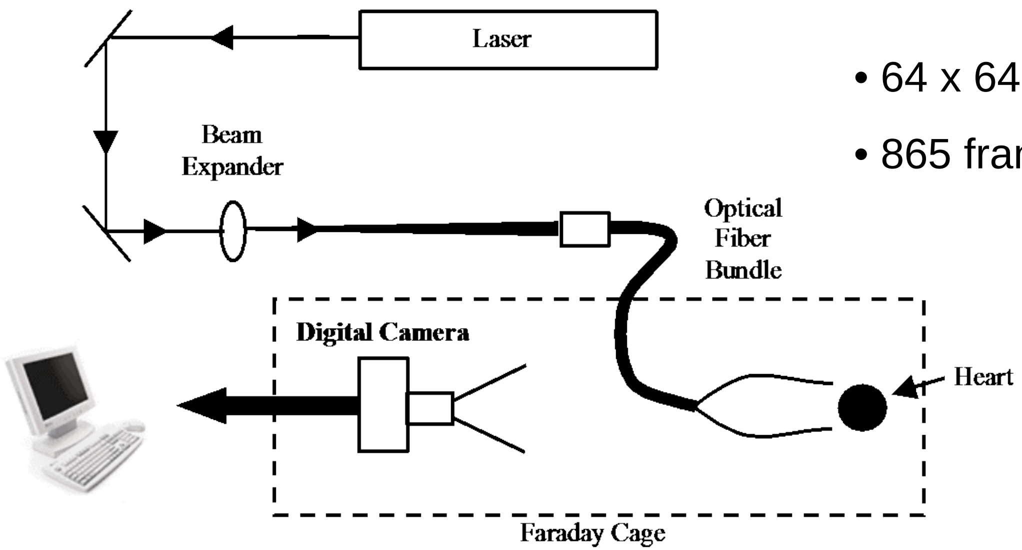
Statement of the General Problem

- The response of cardiac tissue to strong electrical stimulation is critical to understanding the defibrillation process.
- While it is obvious that electrical shocks activate and inactivate regions of the heart distant from the site of stimulation, standard cable models of cardiac tissue predict that such far-field stimulation would be ineffective more than a few millimeters from the stimulating electrode.
- Cardiac heterogeneities are one hypothesized mechanism for far-field stimulation.

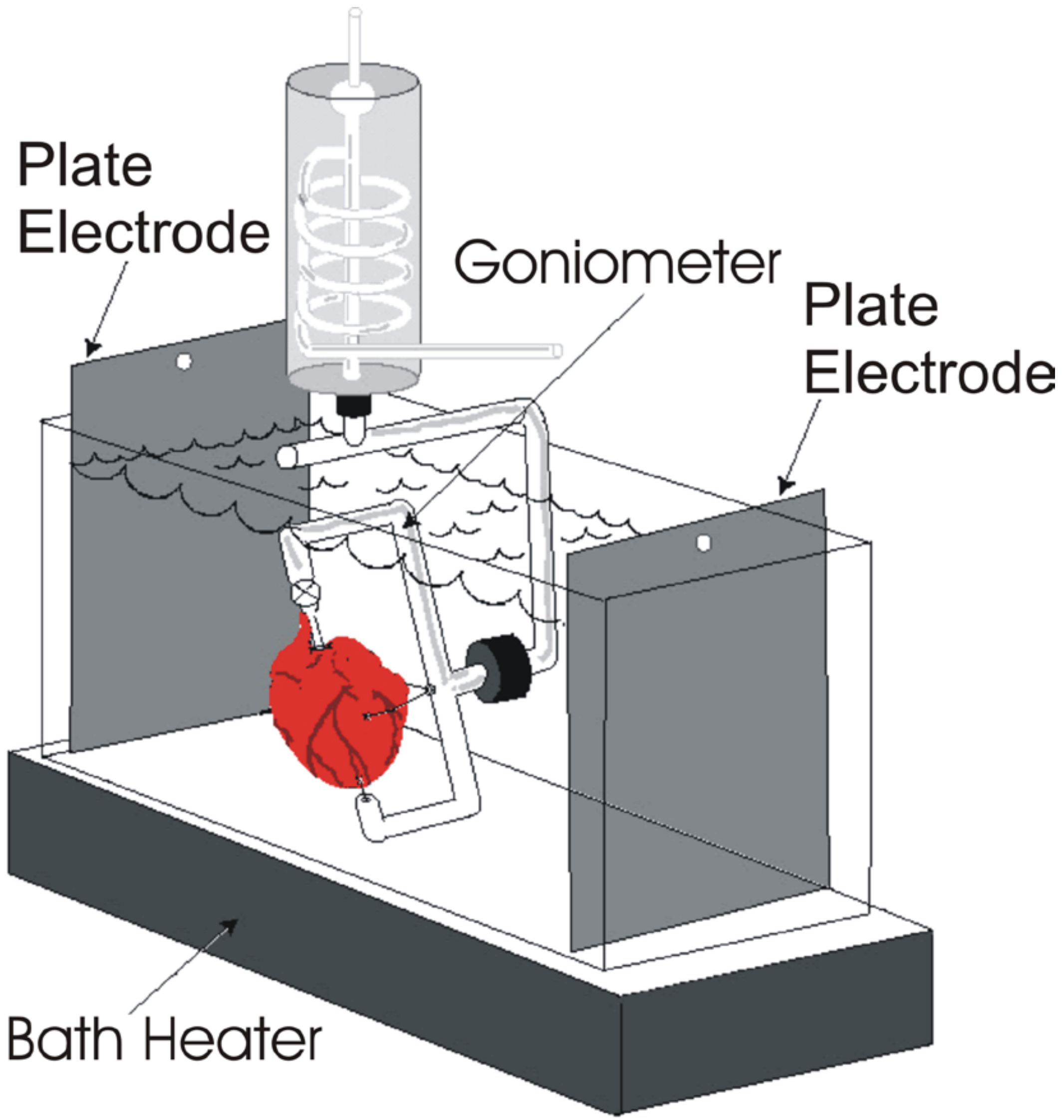
General Methods

- Dye fluorescence imaging of transmembrane potential allows characterization of shock-tissue interaction.
- Isolated rabbit hearts are Langendorff-perfused and stained with the fluorescent dye, di-4-ANEPPS.
- Illumination is achieved by a diode-pumped solid state laser.
- Images are acquired with a 12-bit Dalsa CCD camera.

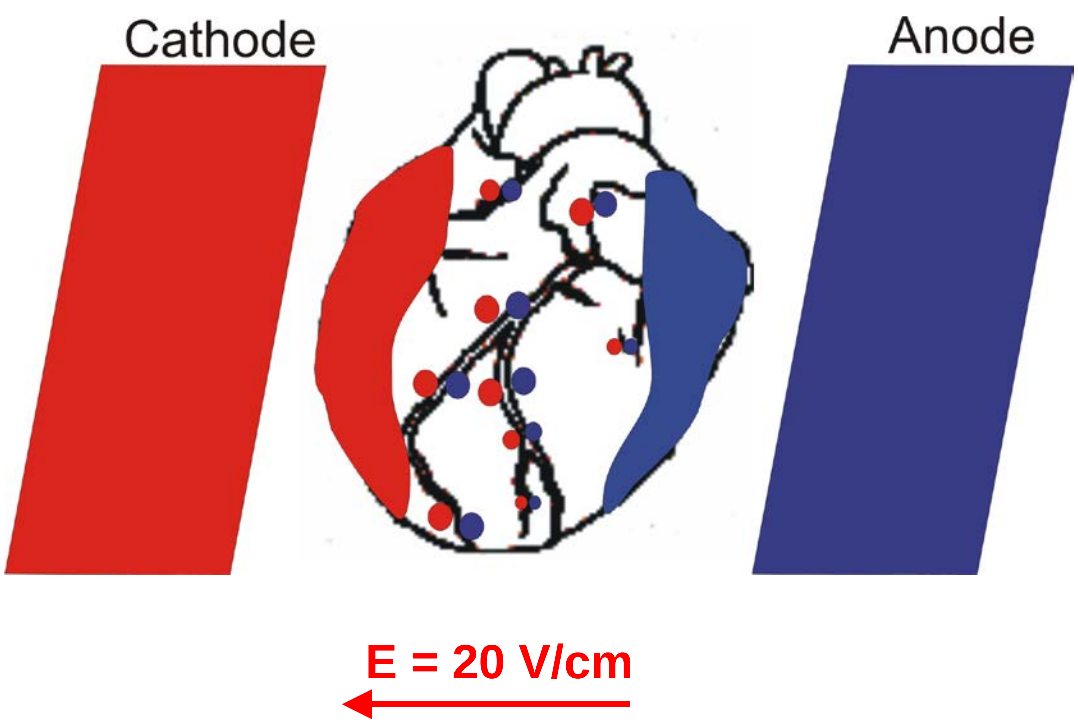


- 64 x 64 pixel resolution
- 865 frames/sec

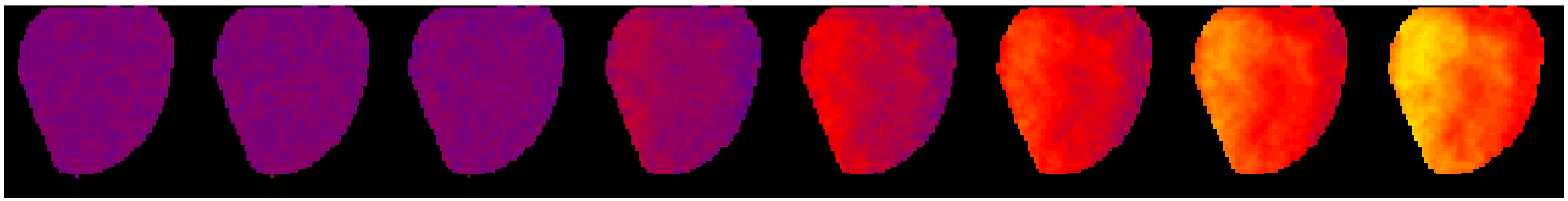
Whole Heart Experimental Setup



Whole Heart Field Shock - Expected



Whole Heart Field Shock - Observed

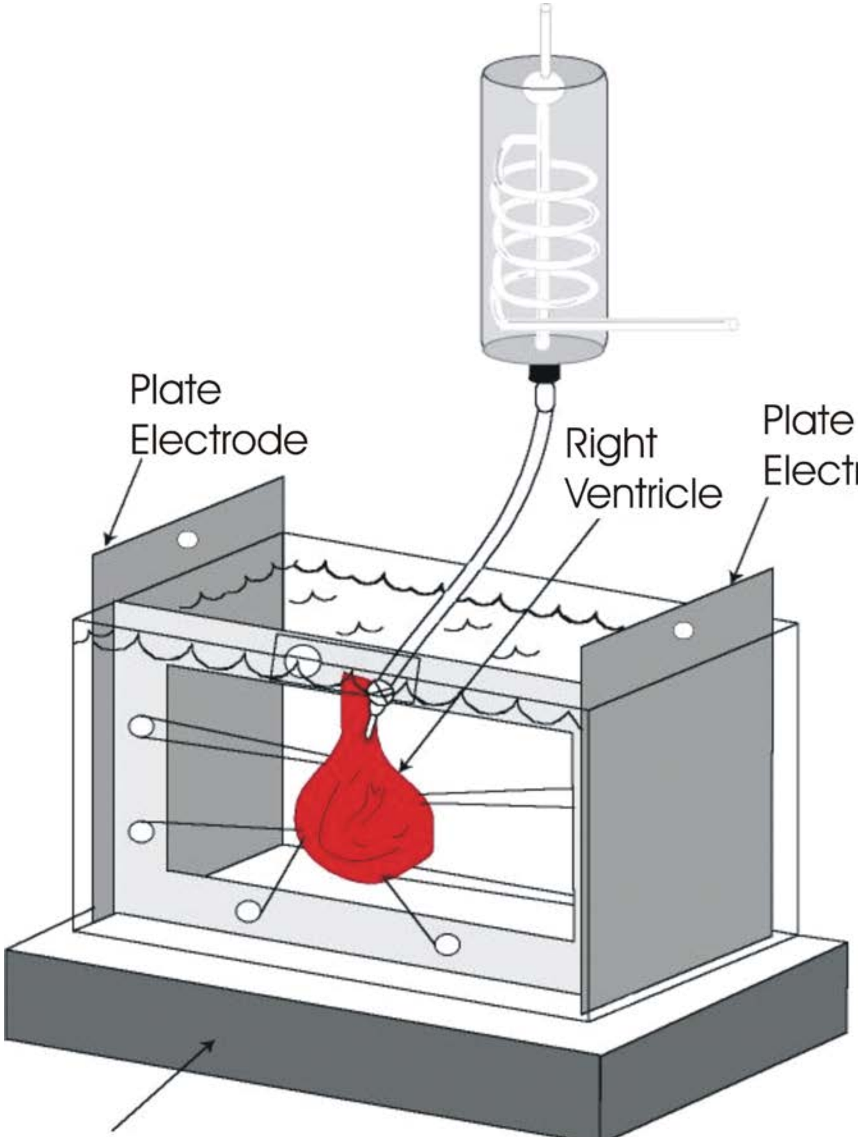


E = 33 V/cm ←

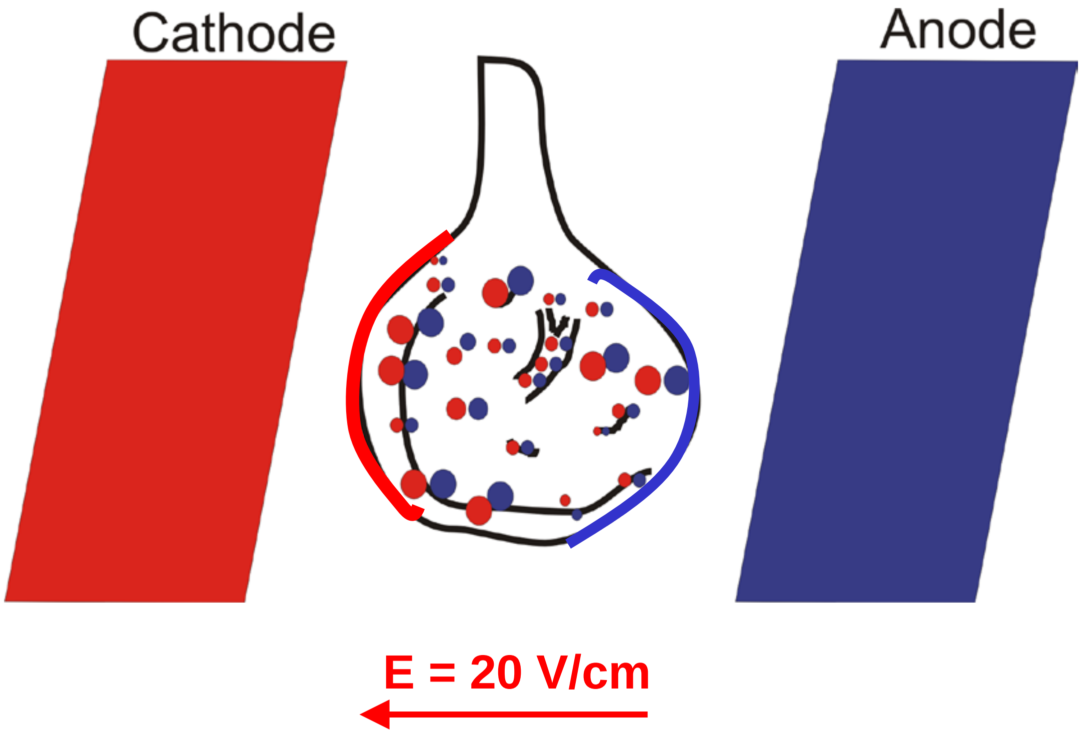
Left/right effect: The side nearer the cathode activates first.

We do not observe hyperpolarization of the side nearer the anode for diastolic field shock.

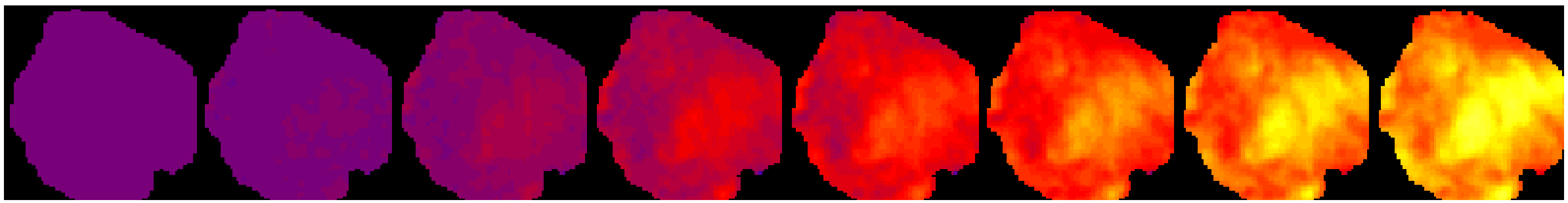
Right Ventricle Experimental Setup



Right Ventricle Field Shock - Expected



Right Ventricle Field Shock - Observed



E = 20 V/cm ←

Endocardial side of preparation in fluid is imaged.

Heterogeneous activation in response to field shock.

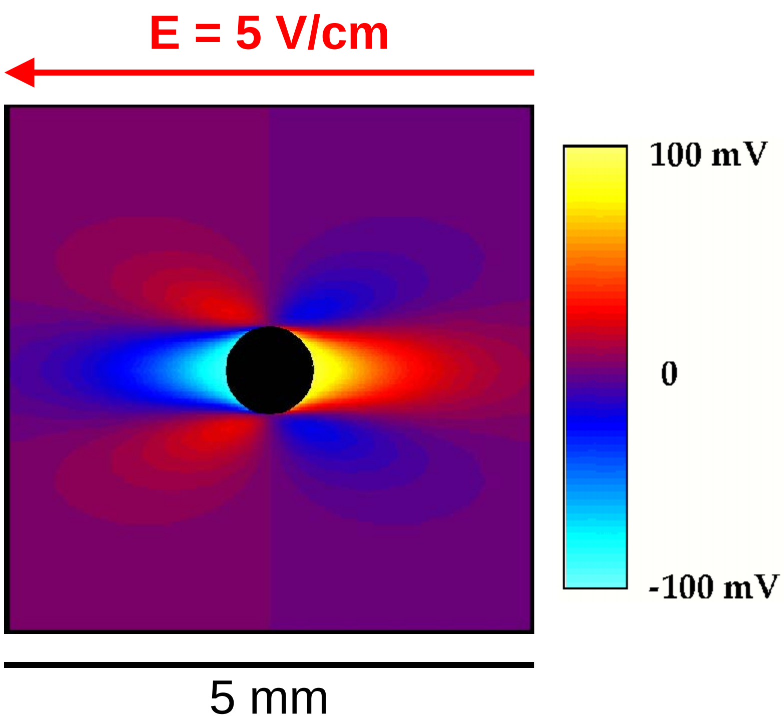
We do not observe virtual cathodes during diastolic field shock.

Where are the anode/cathode pairs associated with heterogeneities during strong field shocks?

Statement of the Smaller Problem

- Plunge electrodes are often used experimentally to record extracellular potentials. These electrodes are artificially-added heterogeneities.
- Numerical simulations (Langrill and Roth, IEEE TBME, 2001) predict alternating regions of depolarization and hyperpolarization surrounding a plunge electrode. In this study we seek to confirm these results experimentally.

Numerical Predictions



Alternating regions of positive and negative polarization around the plunge electrode in response to an electric field.

Horizontal fiber direction

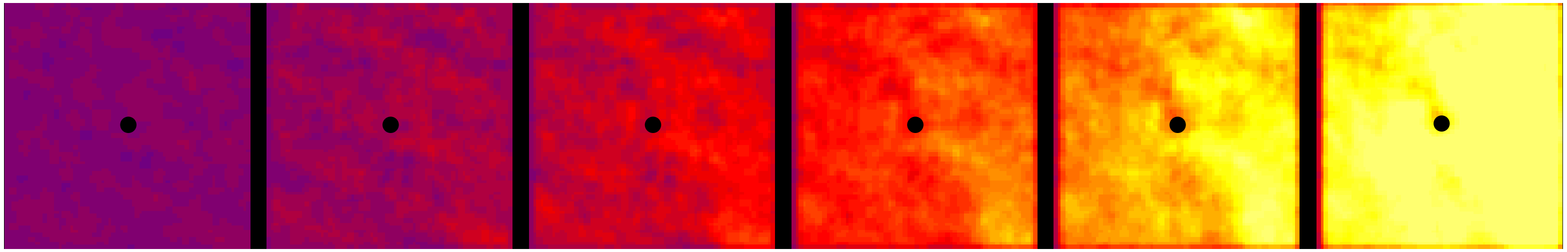
● = 0.8-mm-diameter plunge electrode

Langrill, D. M. and Roth, B. J., "The effect of plunge electrodes during electrical stimulation of cardiac tissue." *IEEE Transactions on Biomedical Engineering*, vol. 48, no. 10, pp. 1207-1211, 2001.

Plunge Electrode Experiment Methods

- The isolated right ventricle preparation is used.
  - Removes the effects of curved boundaries of the isolated whole heart
  - More closely approximates the 2-dimensional numerical simulations
- The epicardial side of the preparation is imaged.
- The preparation is in air, with small plate electrodes along the left and right edges of the tissue.
- Pacing pulses (S1) are applied at a coupling interval of 500 ms.
- Test pulses (S2) 15 ms in duration are applied either to systolic tissue (S1-S2 coupling interval of 100 ms) or to diastolic tissue (S1-S2 coupling interval of 450 ms).
- An insulated 23-gauge hypodermic needle is used to model the plunge electrode.

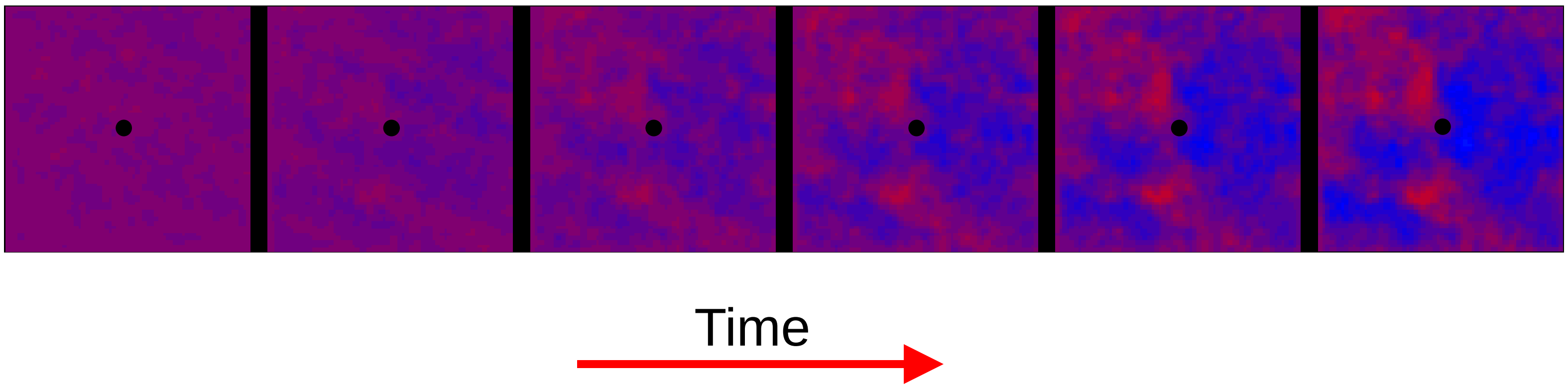
Diastolic Field Shocks



Time →

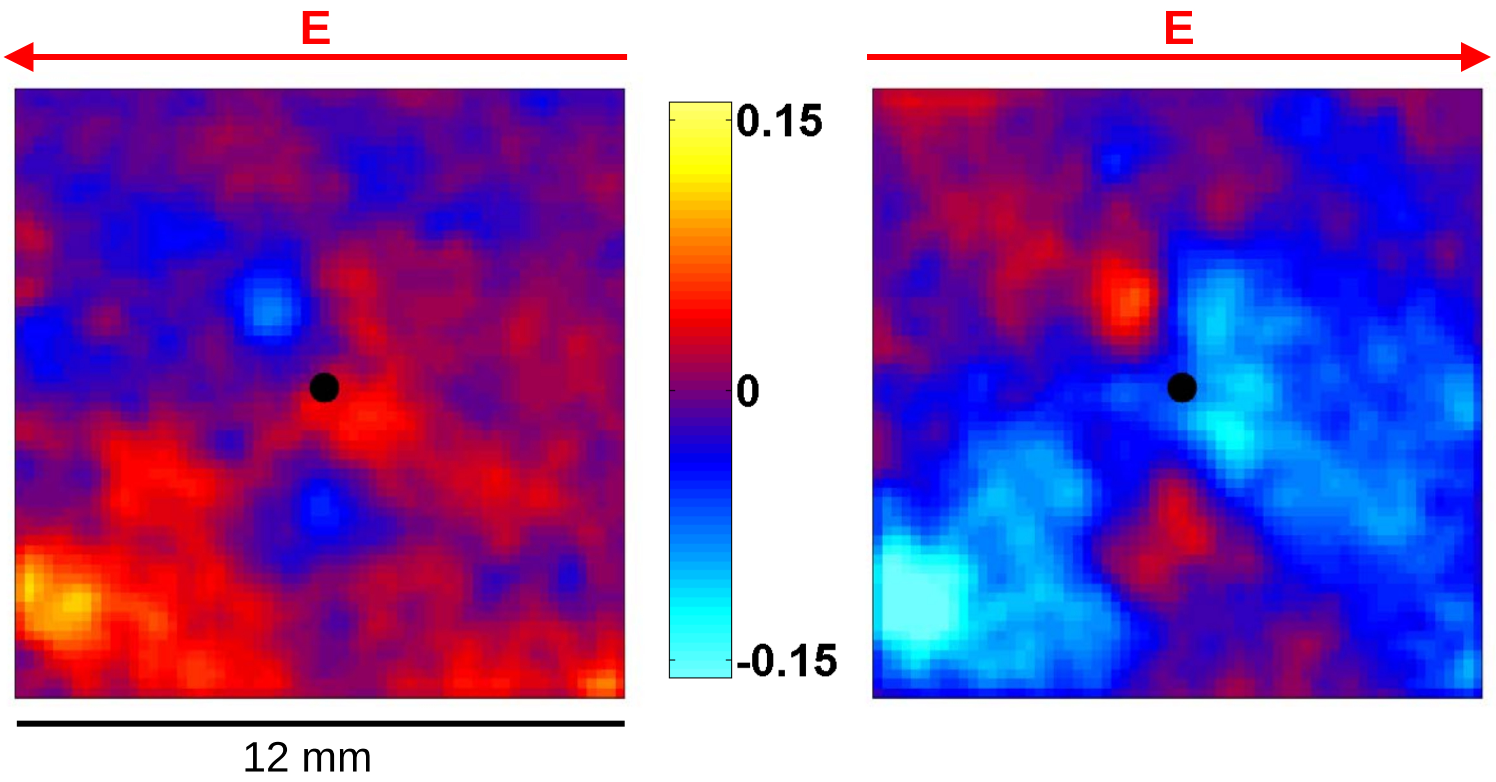
No virtual cathodes or anodes are seen around plunge electrode in RV in air during diastolic field shocks – all we see is a uniform depolarization propagating to the left.

Systolic Field Shocks



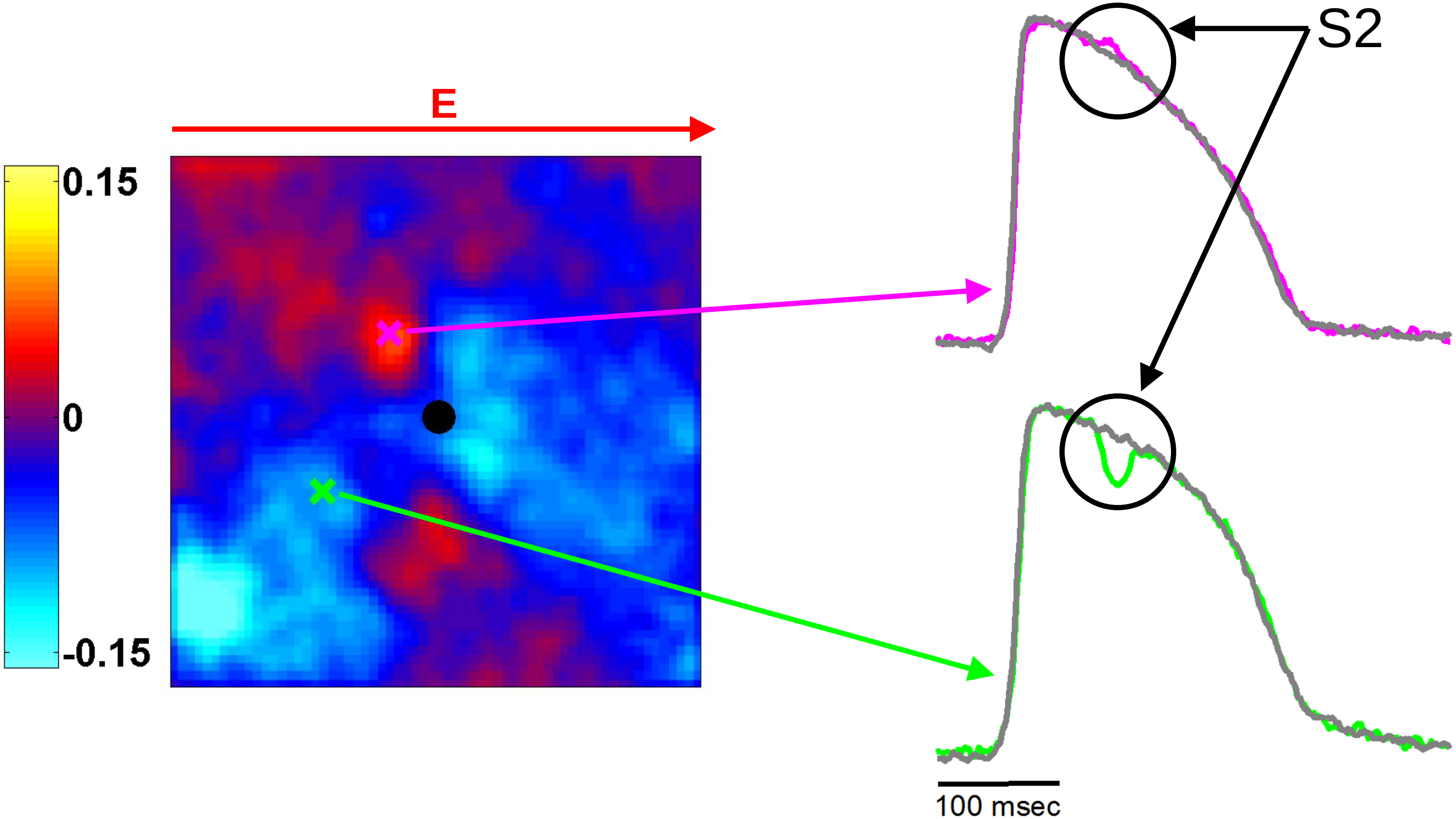
Virtual cathodes and anodes appear around plunge electrode during systolic field shocks in air.

Systolic Shocks: Experimental Results

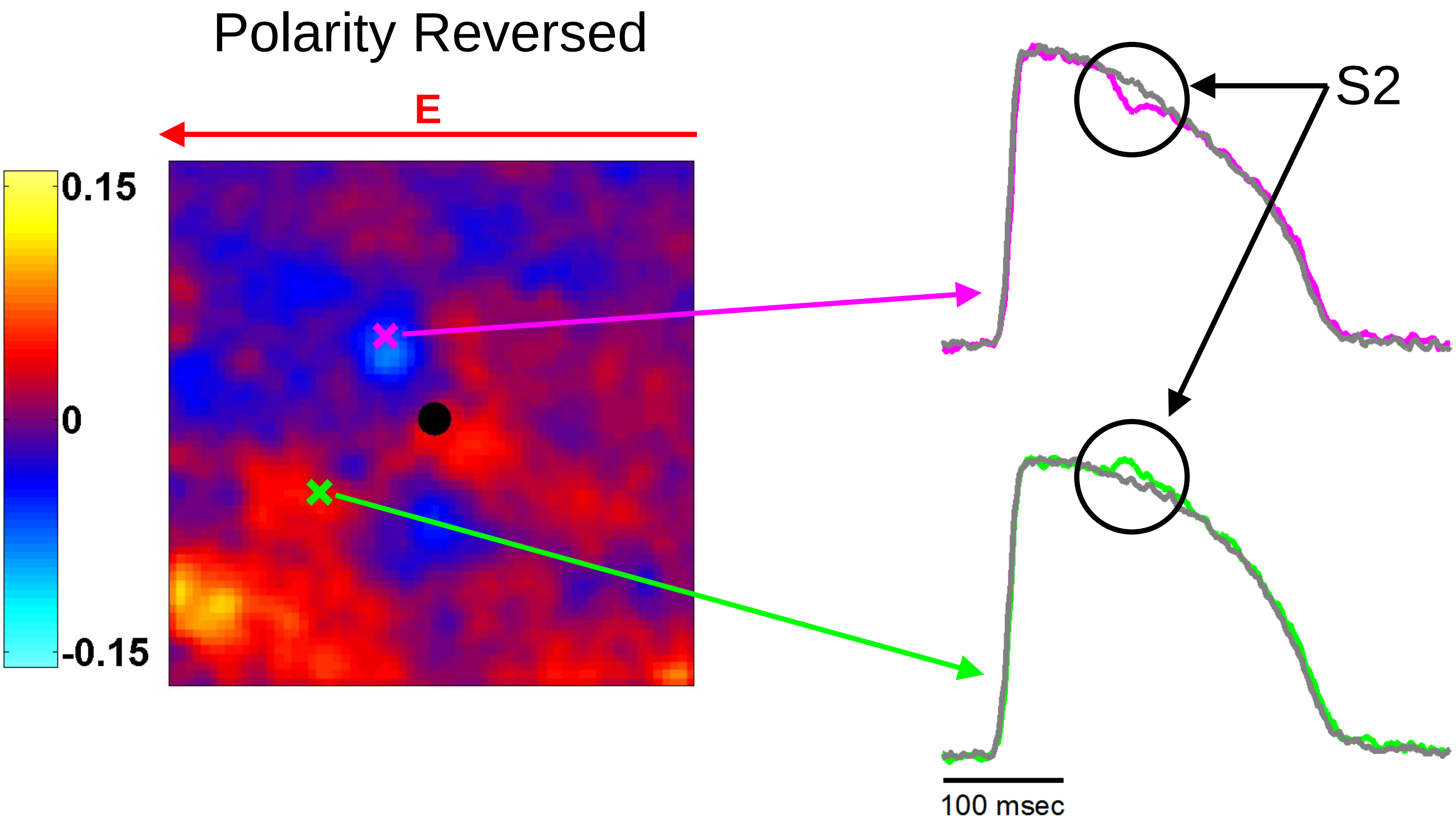


When the field shock polarity is reversed, the polarization pattern also reverses.

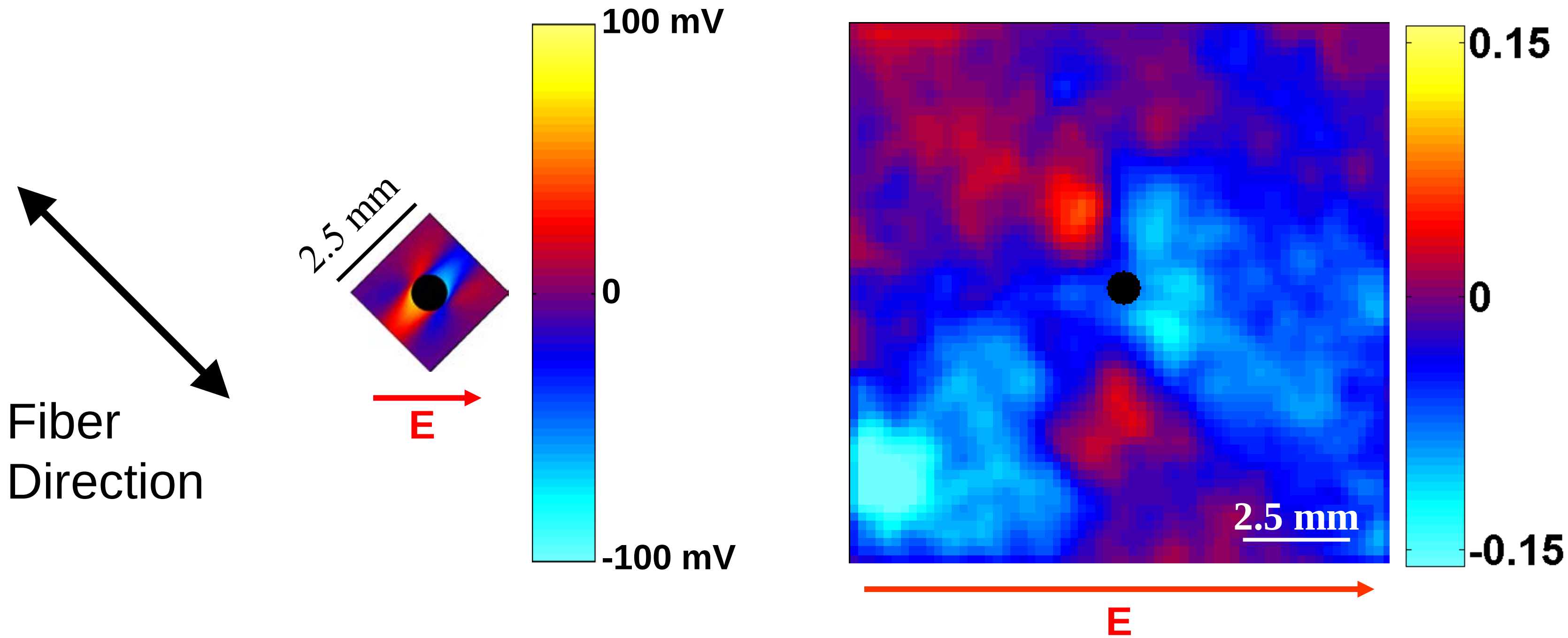
Systolic Shocks: Experimental Results



Systolic Shocks: Experimental Results



Comparison of Theory and Experiment



Qualitative agreement between theory and experiment for systolic field shocks.

The spatial scale of the induced polarization is the major discrepancy.

Observations

- Anode/cathode pairs do not occur for diastolic field shocks.
- There is qualitative agreement between the numerical predictions and experimental results for systolic field shocks.
- The major discrepancy is the spatial scale over which the effect occurs.
  - Ischemia caused by inserting hypodermic needle
  - Combination of fast transmural fiber rotation in the right ventricle and fluorescence averaging over depth

Conclusions

- The virtual anodes which are theoretically associated with heterogeneities are not observed for diastolic field shocks.
- Plunge electrodes are artificially-added heterogeneities that can induce a transmembrane potential distribution in response to a systolic electric field.
- The induced adjacent areas of opposite polarization are a potential source of wave front generation, and may be one cause of far-field stimulation.
- Therefore, in experiments using plunge electrodes or other similar heterogeneities, it should not be assumed that these heterogeneities have no influence on the heart’s response to electrical stimulation.

Future Work

- The experiment will be repeated in a bath whose conductivity matches that of the cardiac tissue to obtain a uniform electric field.
- The electric field will be applied at different orientations relative to the fiber direction.
- More complex numerical modeling of the problem will be performed to incorporate three-dimensional tissue, transmural fiber rotation, and fluorescence averaging over depth.

Acknowledgments

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