The Role of Higher Order Scroll Wave Filament Dynamics in Terminating Fibrillation

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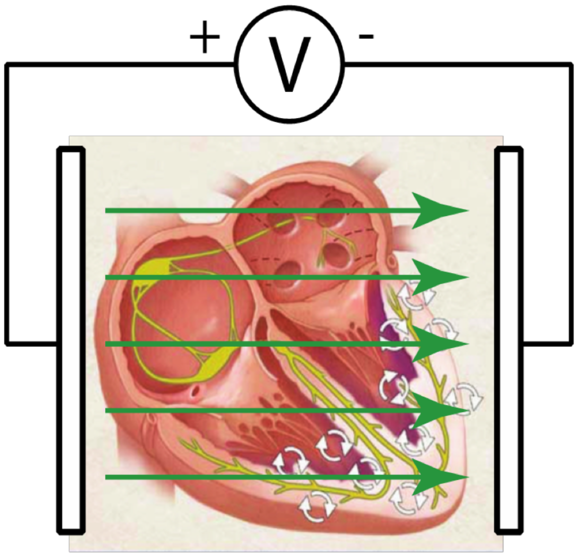
Introduction

There is currently interest in developing a **low-energy, electric-field-based defibrillation method**.

Such methods would be:

1. Less painful and traumatic for the patient,
2. Less damaging to the heart and surrounding tissue, and
3. Less of a drain on the battery (when the defibrillator is implanted).

Here we explore a new idea that may be useful for these methods.

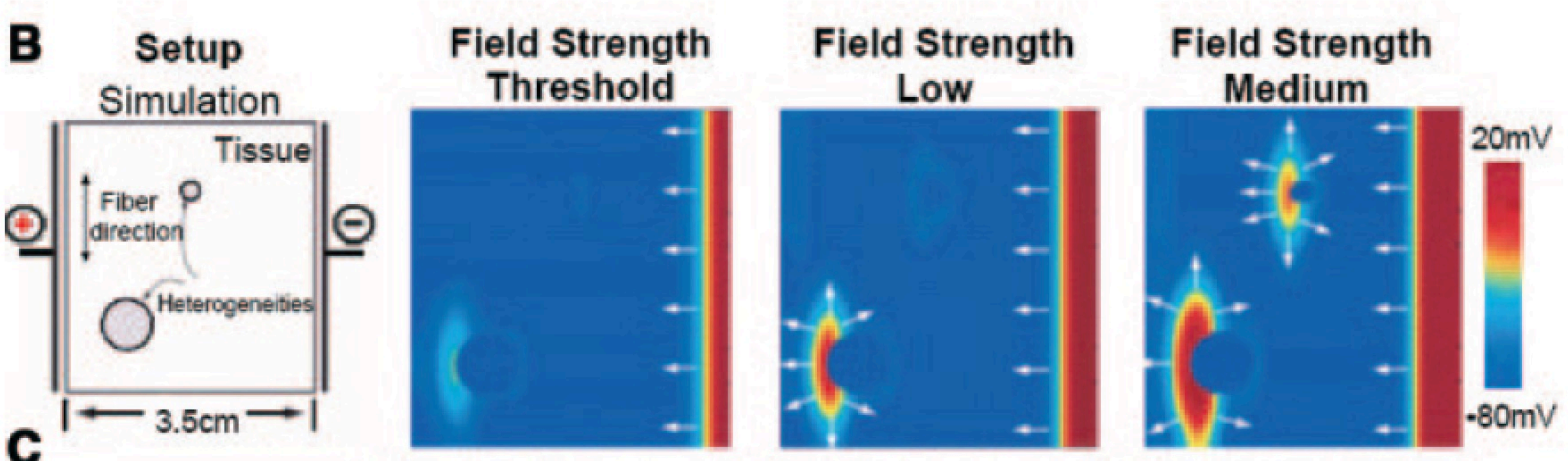


Introduction

Electric-field-based defibrillation:

1. Depolarizes and hyperpolarizes surfaces at very low energy,

2. Also depolarizes hyperpolarizes heterogeneities at slightly higher energies



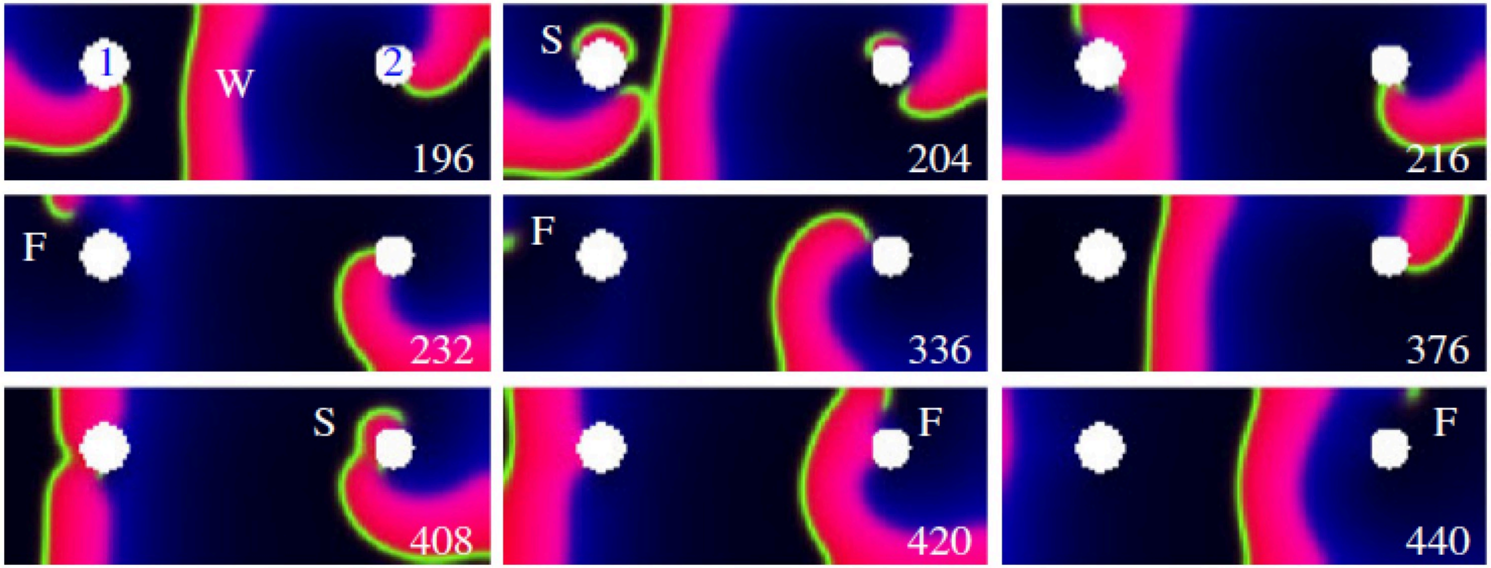
From: F. H. Fenton, S. Luther, E. M. Cherry, N. F. Otani, V. Krinsky, A. Pumir, E. Bodenschatz and R. F. Gilmour, Jr., Circulation 120, 467-476 (2009).

Here we focus on surface depolarization, which is possible with very low E-fields.

Introduction

Most studies in this area are 2-D in nature.

- Requires knowledge of the **phase** of the reentrant waves (not usually known):



From: D. Hornung, V. N. Biktashev, N. F. Otani, T. K. Shajahan, T. Baig, S. Berg, S. Han, V. I. Krinsky and S. Luther, Royal Society Open Science 4, 170024 (2017).

Introduction

Here we propose an inherently 3D method that requires no knowledge of the reentrant waves':

a. Phase,
b. Location, or
c. Sense of rotation.

The method also works with **any number** of waves, simultaneously.

However, this new idea has its own **limitations**…

Computer Model

We model electrical wave propagation with the Barkley equations:

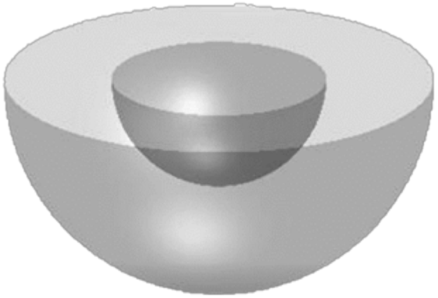
$$\frac{\partial u}{\partial t} = D\nabla^2 u + \epsilon^{-1} u(1-u)(u-(v+b)/a)$$
$$\frac{\partial v}{\partial t} = u - v$$

which are advanced in time using a simple forward Euler method.

Parameters: $a = 0.8$, $b = 0.05$, $\varepsilon = 0.02$, $D = 1$.

Simulations are conducted in either

- A **3D cylinder** or
- 3D **hemispherical shell** (shown on right).

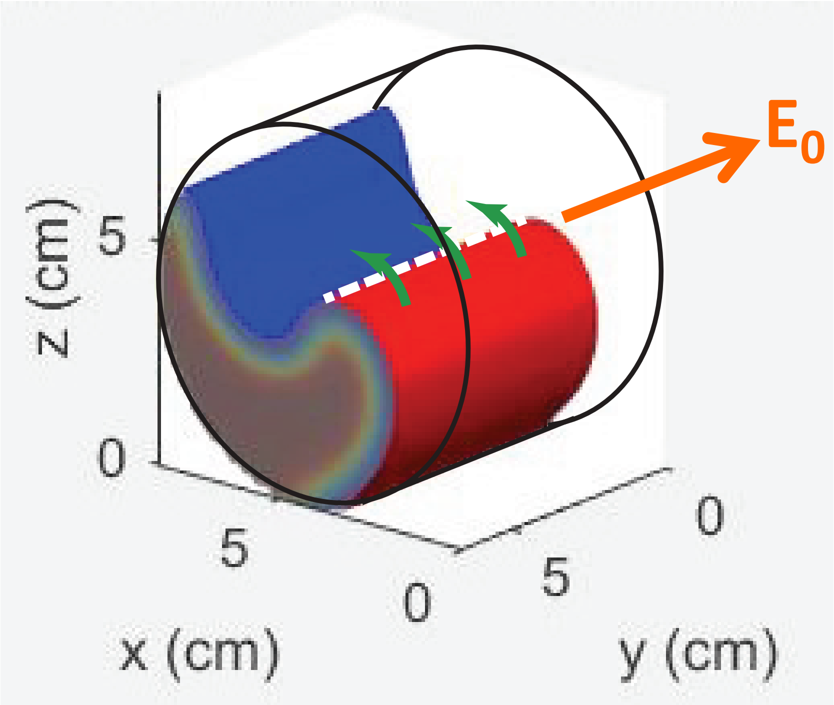


The idea

The new mechanism arises from **3 key concepts.**

Consider a reentrant wave in a cylindrical system.

- Apply an electric field pulse parallel to the filament.
- **Filament** = axis of rotation of the rotating wave.

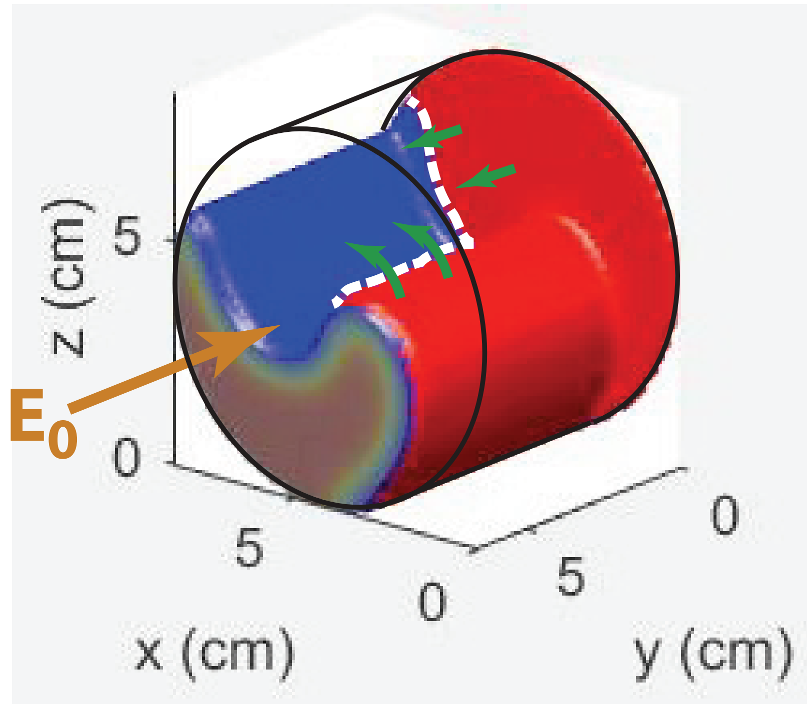


The idea

First key concept:

Weak electric fields (~1 V/cm) can detach filaments from the surfaces they depolarize.

- The electric field depolarizes the rear surface, launching a new wave.
- The result is an L-shaped filament.



V. Biktashev, PhD Thesis. (1989).

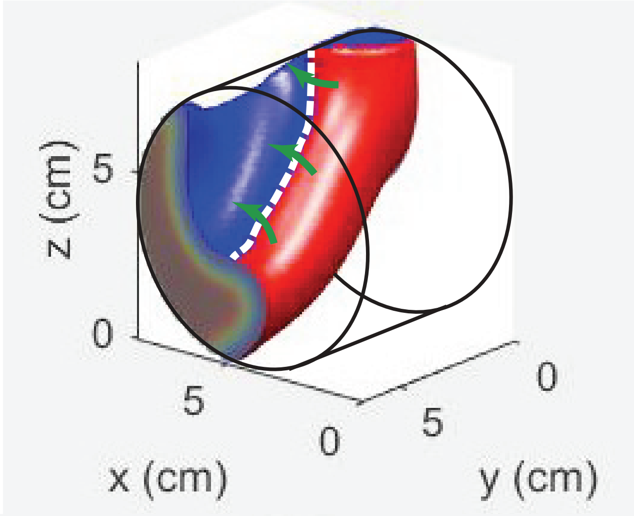
C. Zemlin, S. Mironov, A. Pertsov, J. Cardiovasc. Physiol. 14, S257 (2003).

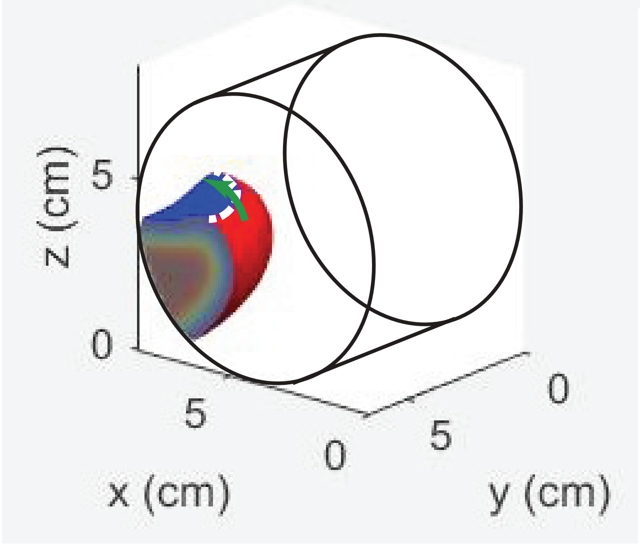
The idea

Second key concept:

Detachment results in a filament that is "L-shaped", then, "C-shaped," which then shrinks and disappears.

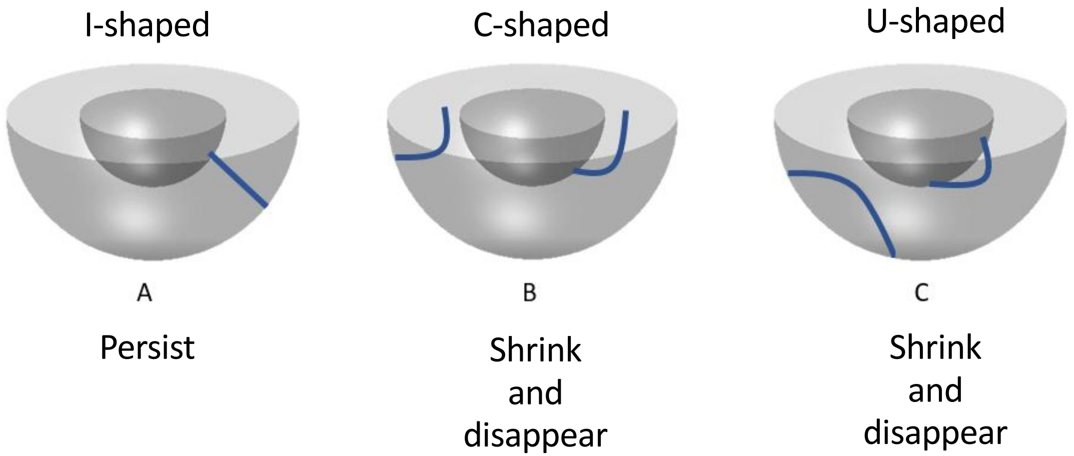
Note: In general, filaments with fundamentally curved shapes (L, C, U or O-shaped) tend to shrink and disappear, in the so-called positive tension regime.





The idea

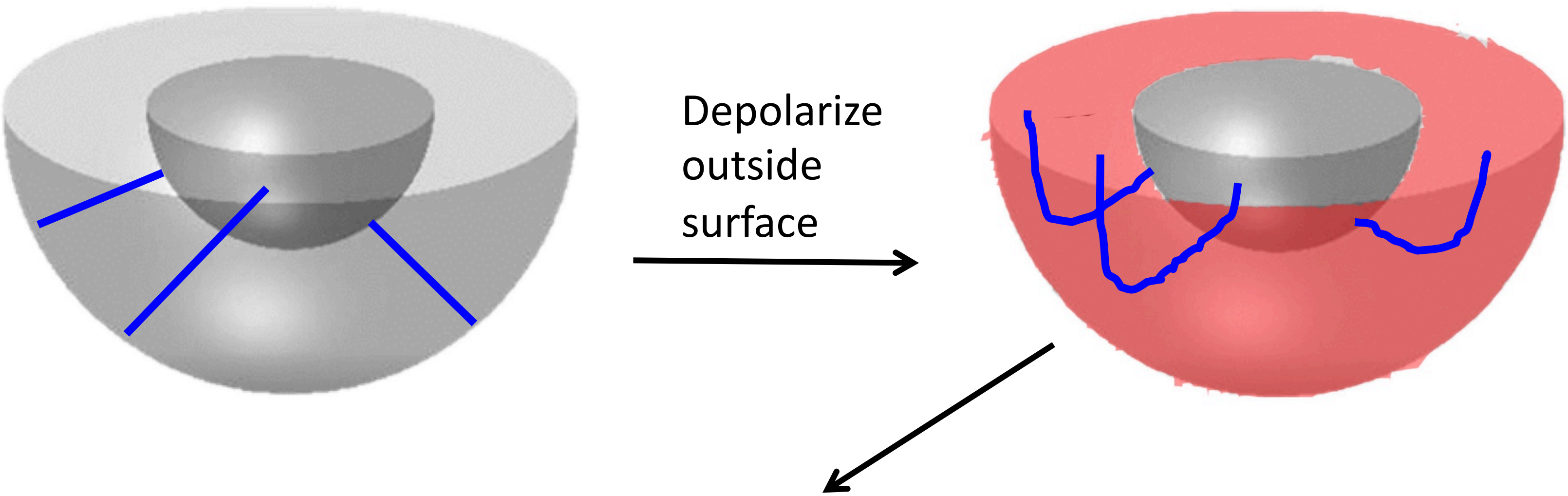
However, I-shaped filaments cannot shrink, and therefore cannot disappear:



Idea

Third key concept: Configure the electric field pulse so that the detachment of all filaments from the surface it depolarizes renders all the filaments C-shaped, U-shaped or O-shaped.

An outward radial field does this, for our hemispherical system:



All filaments are converted into C-shaped or U-shaped filaments! These should all shrink and disappear.

Computer tests of the idea

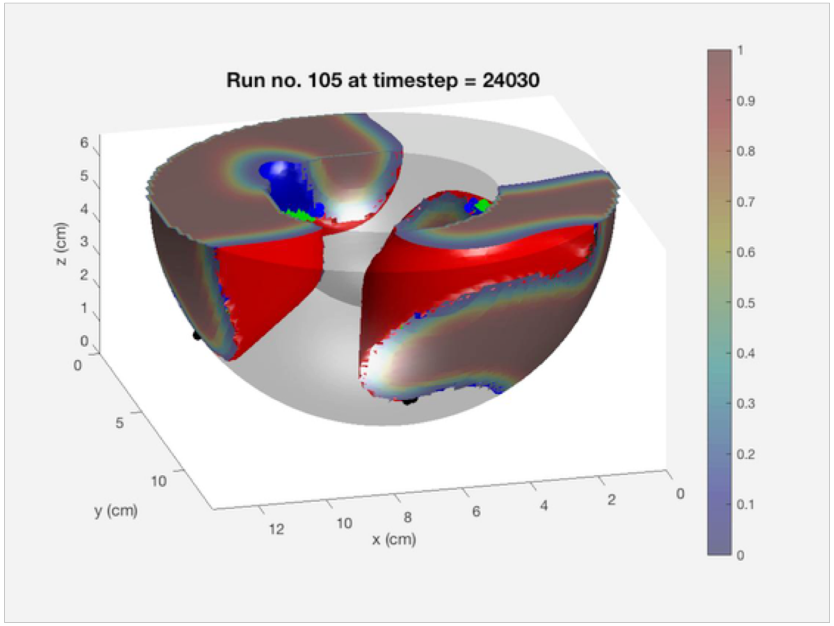
Example: System initiated with 5 reentrant waves.

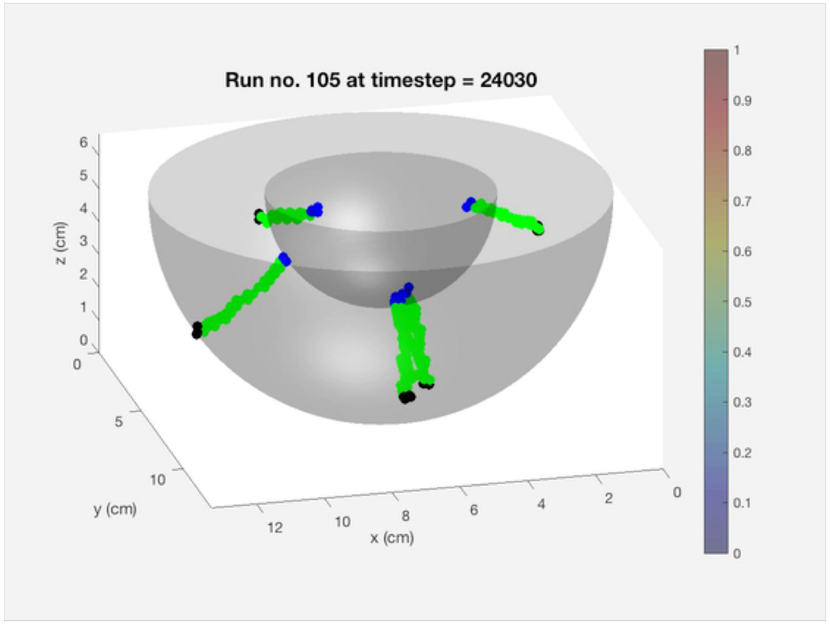
Radial stimulus: 0.92 V/cm.

Filaments are detached from the outer surface.

2 U-shaped and 1 C-shaped filaments remain after the stimulus.

These filaments shrink and disappear.

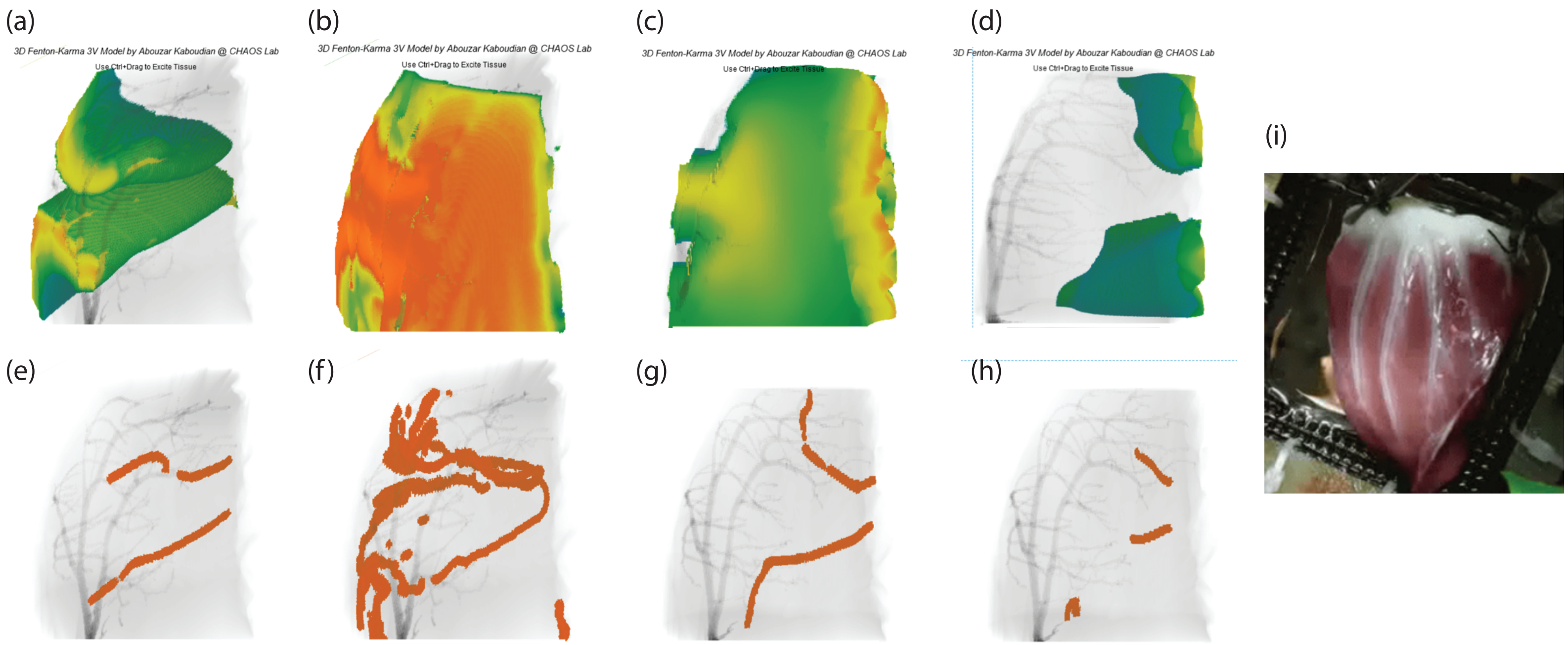




Computer tests of the idea

Simulation of canine left ventricular free wall.

(Courtesy: Claire Ji and Flavio Fenton, Georgia Tech):

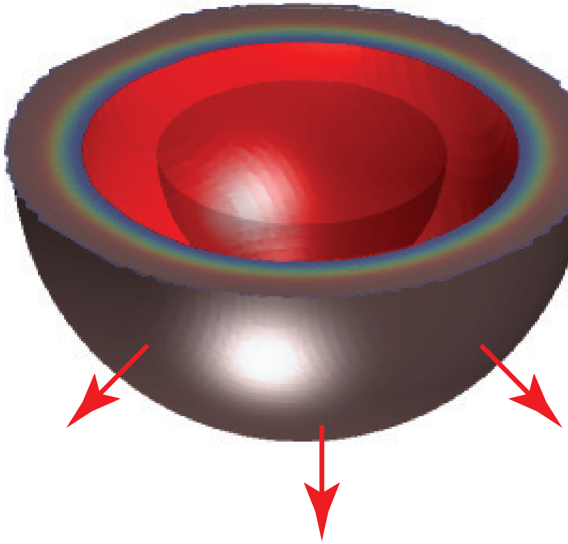


Computer tests of the idea

To further test this idea, we tried two similar electric field configurations:

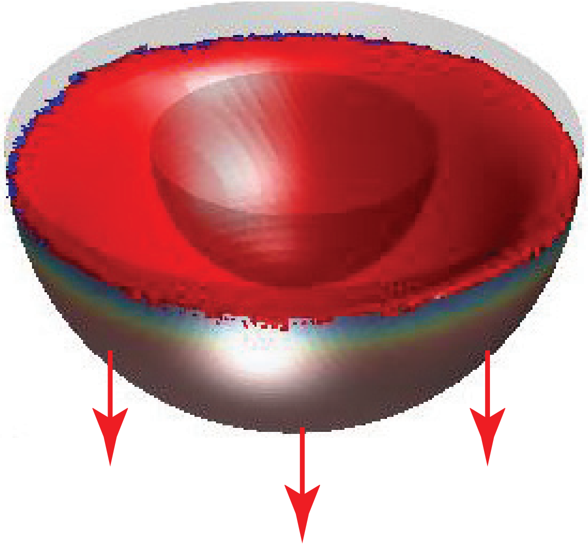
<u>Radial field</u>

Depolarizes the entire outside surface



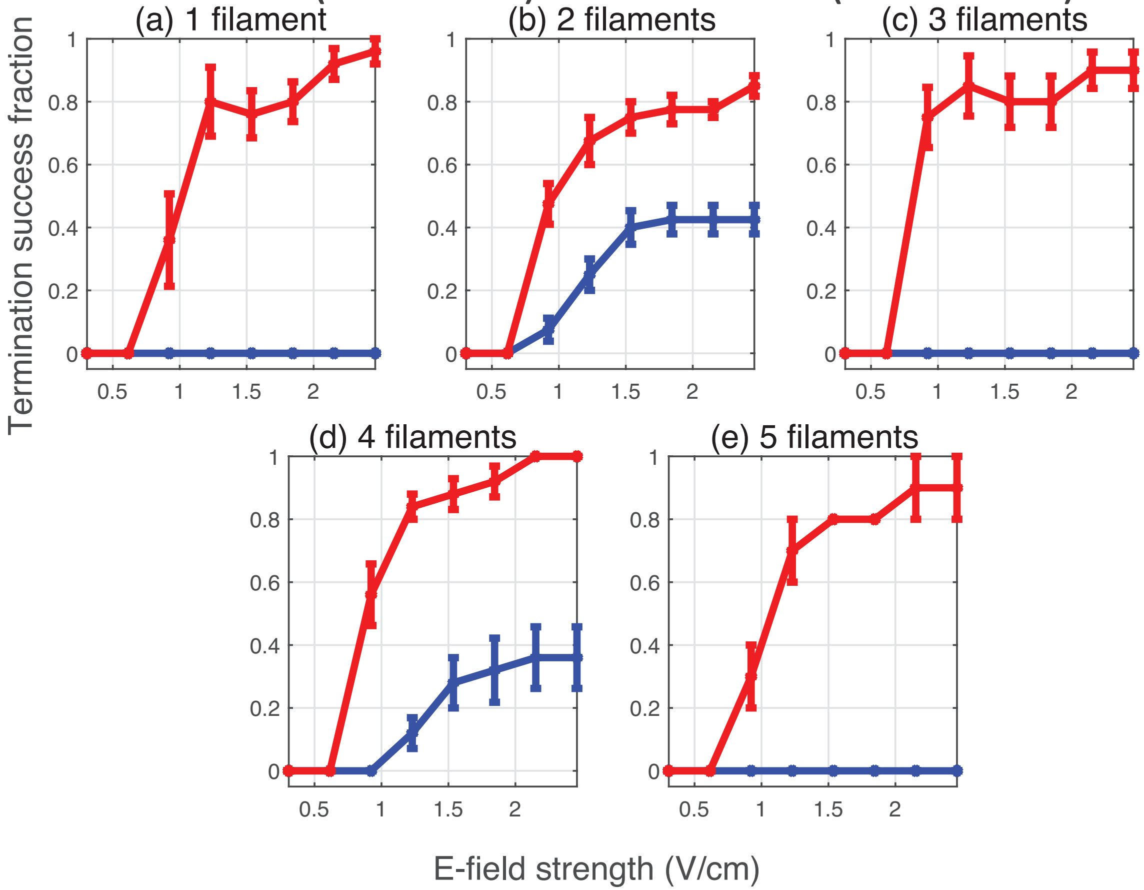
<u>Axially directed field</u>

Does not depolarize the entire outside surface



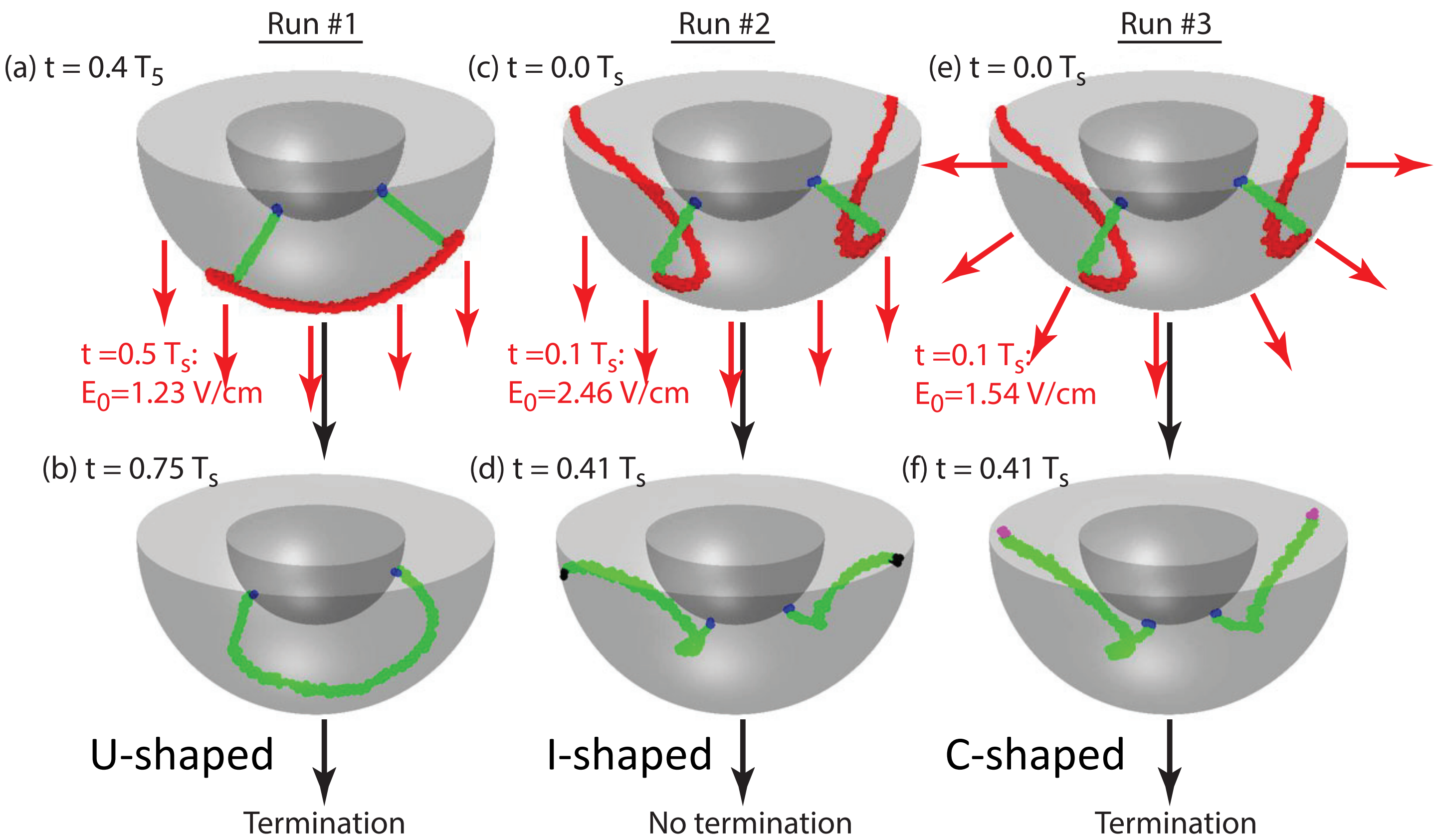
Computer tests of the idea

Ran 1920 simulations: 24 different initial conditions containing 1 to 5 reentrant waves, with one of 8 E-field strengths, one of 5 E-field timings, with either a radial field (red trace) or axial field (blue trace):



Computer tests of the idea

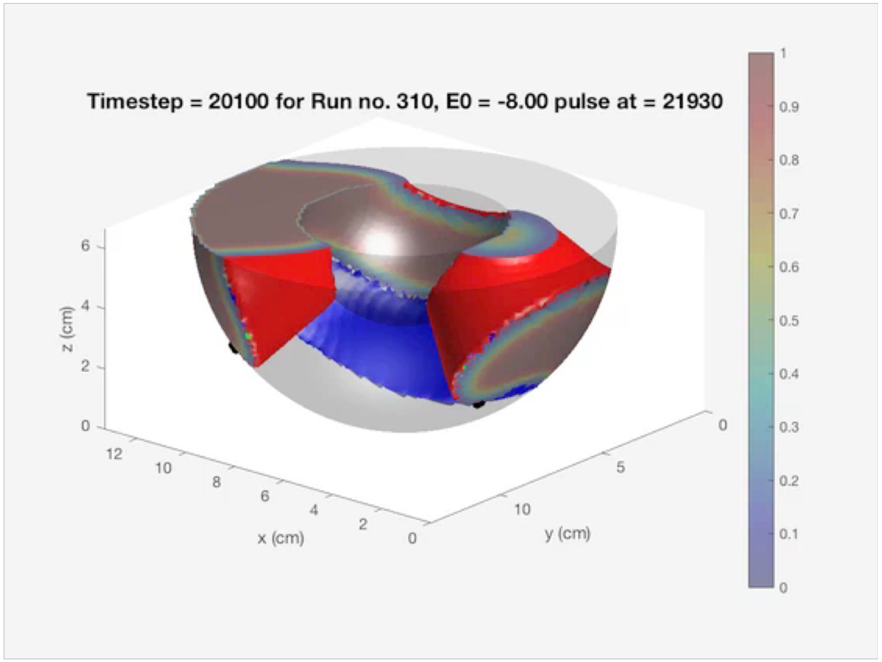
Instructive cases: Red trace is the intersection of the waveback and induced depolarization on the outer wall.

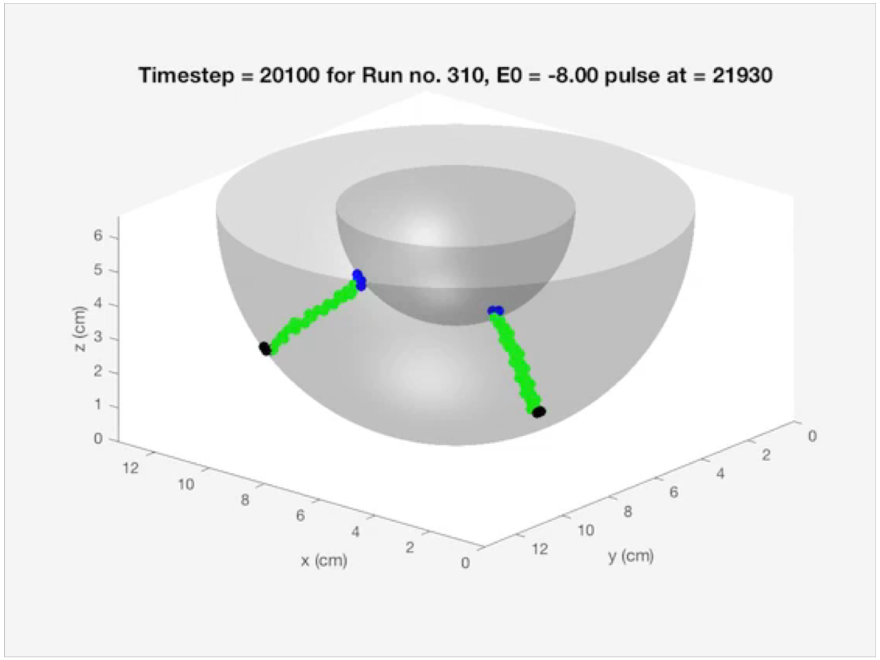


Behavior not explained by filament tension

An important example of behavior not explained by filament tension is the case of an inward-pointing radial electric field pulse.

As opposed to outward radially-directed E-pulses, inward pulses generally fail to terminate scroll waves:

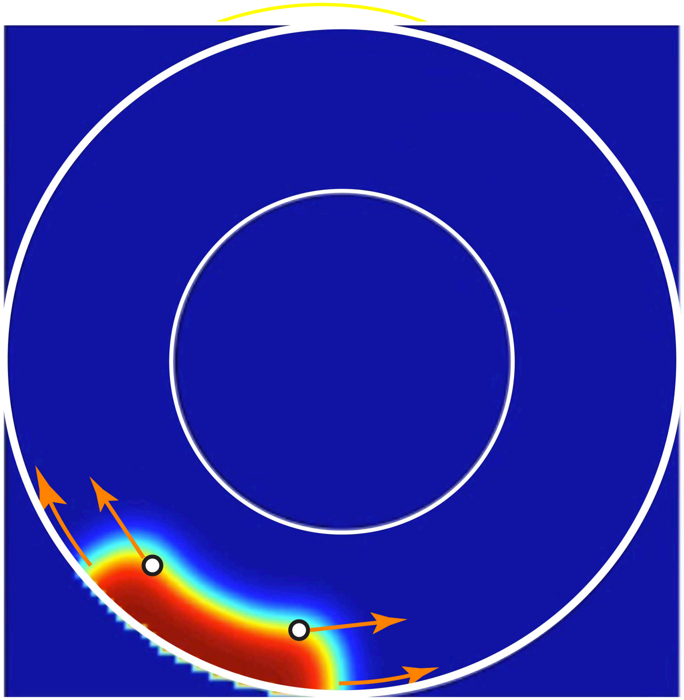




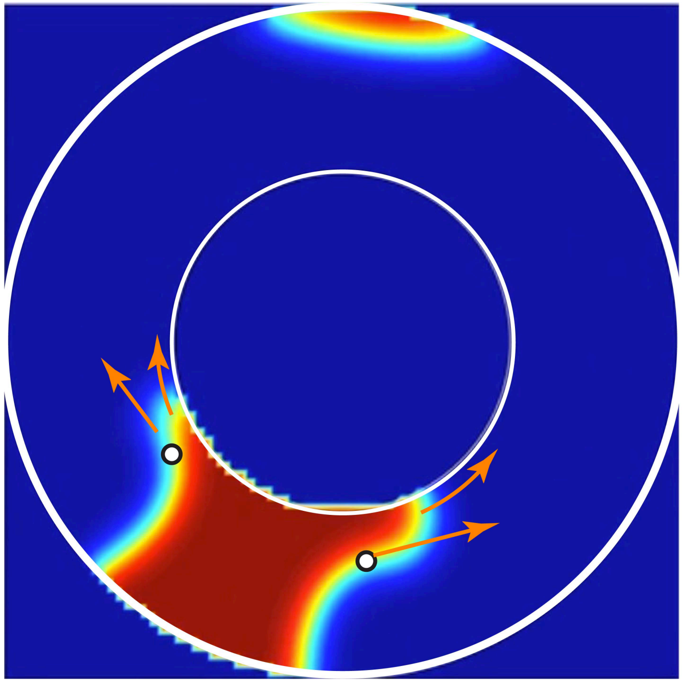
Behavior not explained by filament tension

Reconnection of filaments to the inner surface may be due to failure of the wave to a source-sink mismatch while rotating around a point on the top surface.   Top surface views:

Source-sink balance on the outer wall (after outward E-pulse):



Source-sink mismatch on the inner wall (after inward E-pulse):



Limitations

This new defibrillation idea has many limitations, which we will explore in the future:

1. Positive filament tension is likely required,
2. Wave breakup due to alternans or other instabilities may be a competing effect,
3. Rotational anisotropy of the fiber directions with location may modify these results.
4. More higher-order filament motion should be considered.
5. At somewhat higher field strengths the presence of other virtual electrodes may complicate the effect.
6. As we have seen: Boundary curvature seems to be relevant.

Conclusions

1. We describe a new idea for terminating multiple reentrant waves, which requires no knowledge of:
   a. how many waves are present,
   b. the location of the waves,
   c. their phases, or
   d. their sense of rotation.
2. The idea combines three mechanisms:
   a. Electric field pulses that that are not parallel to a surface can detach filaments from that surface,
   b. Fundamentally curved filaments tend to shrink and disappear and,
   c. For heart-like geometries, there exist electric field configurations that can force all filaments into this type of curvature (i.e., C-shaped, U-shaped or O-shaped filaments).

Conclusions

3 Boundary curvature renders inward radial fields ineffective, when a filament tension argument would suggest otherwise.

4 I believe this is an important idea, but it has significant limitations. Thus, it should be considered alongside other ideas currently being investigated in developing low-energy defibrillation. The successful low-energy technique will likely be based some combination of these ideas, modified as required to deal with the various limitations they all possess.

Questions?