Abstract
A simplified quantitative ionic model of cardiac action potential, which reproduces accurate restitution curves, is used in conjunction with global tissue characteristics such as rotational cell anisotropy and periodic boundaries to study the transition from ventricular tachycardia (VT) to ventricular fibrillation (VF). We give an explanation for the experimental observation that there is a minimum tissue mass required for this transition to occur.

Restitution Curves
In cardiac tissue it is possible to define two characteristic curves that describe how the duration and conduction velocity of a wave depend on the time interval since the previous activation, during which the medium recovers its resting properties. This restitution functions thus reflect the electrophysiological state as well as tissue characteristics.

The collision of incoming waves, with a higher frequency than the one of rotation, produces a drift on the spiral. This drift is proportional only to the ratio between the cylinder’s perimeter and the length of the wave-tip trajectory (core).

For spiral waves in the hyper-meander regime, there is a window of parameters: the ratio between the diameter and the number of cycles before termination, for which otherwise stable spiral waves break. The breakup is produced by conduction blocks between the spiral wave tip and self incoming waves generated by uneven regions of repolarization due to the hyper-meander tip.

Conclusions
Spiral breakup due to periodic boundary conditions may be present in normal hearts when a hypermeandering spiral wave is generated (or drifts) close to the apex where the perimeter of the heart is small. Also, the anisotropic fiber architecture of the left ventricular wall is a major predisposing factor for the degeneration of VT to VF.

Our numerical simulations have demonstrated that transmural fiber rotation causes 3D scroll waves to become unstable and to spontaneously decay into wave turbulence above a minimum wall thickness comparable to the one observed in some experiments [4].

Initiation of Spiral Waves by a Premature Stimulus
Numerical simulation. Panels A–B’ premature stimulus (S2) applied too soon, the tissue behind the plane wave is refractory and the stimulus dies out. Panels A–B”, S2 applied too late, the tissue is readily excitable and the stimulus produces a target pattern wave. Panels A–L, S2 successfully applied during the window of vulnerability producing two mirror image spirals waves of action potential.

The parameters of the model can be varied to reproduce arbitrary (experimental and numerical) APD and CV restitutions. Different restitutions produce different dynamics on spiral waves. For example the transition from linear core to circular core trajectories can be produced by changes in sodium and/or calcium currents. For example, the following graph shows this transition using the 3V-SIM fitted to the modified Beeler-Reuter ionic model where the sodium current increases from right to left.

The top figure shows breakup of a spiral wave (fitted to the MBR) on a cylinder (unfolded where the vertical boundaries are periodic) with a 4 cm diameter. Note that the spiral would be stable on a larger tissue or on the same size tissue but with zero flux boundary conditions.

3D and Rotational Anisotropy
The top figure shows breakup of a spiral wave (fitted to the MBR) on a cylinder (unfolded where the vertical boundaries are periodic) with a 4 cm diameter. Note that the spiral would be stable on a larger tissue or on the same size tissue but with zero flux boundary conditions.

The summary of simulation results using the 3V-SIM fitted to the modified Beeler-Reuter ionic model where the sodium current increases from right to left.

The following are 3D snapshots showing the main creation event of vortex lines that lead to the decay of VT into VF under this framework. The bottom surface shows the voltage activation at the endocardium. As the vortex elongates it touches the boundaries forming extra half rings which expand and produce new vortices and a complex spatiotemporal activity.

The propagation of twist along a vortex filament and its drift is proportional only to the ratio between the cylinder’s perimeter and the length of the wave-tip trajectory (core). For spiral waves in the hyper-meander regime, there is a window of parameters: the ratio between the diameter and the number of cycles before termination, for which otherwise stable spiral waves break. The breakup is produced by conduction blocks between the spiral wave tip and self incoming waves generated by uneven regions of repolarization due to the hyper-meander tip.

For thin slabs with small rotational anisotropy stable scroll waves behave similarly to spiral waves in 2D. However, as the rotational anisotropy and thickness are increased the vortex lines can elongate and curve due to a highly localized twist induced by the fiber rotation. These elongated vortices collide with the tissue boundaries and produce a wave breakup which leads to multiple waves characteristic of VF. First top figure shows the nature of the vortex twist, where we plotted the contour and trajectory of a spiral wave in 3D (fitted to other models) and the field of orientation angle of the fibers.

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