Automatic paired Re-entry Detection in Atrial Tachycardia by Topological Analysis of Phase Defects

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Introduction: Atrial tachycardia (AT) is predominantly driven by re-entry circuits that rotate faster than the natural heart rhythm, causing tachycardia. Previous work showed that the sum of all topological charges must equal zero, resulting in pairs of re-entries with opposite charge that can be terminated by an ablation line connecting their rotation centers. We propose a fully automated method to detect paired circuits and suggest optimal ablation strategies.
Methods: Re-entry circuits consistently encircle phase defects, defined as regions where the phase field is discontinuous. Topological charge is computed by integrating phase gradient ($\nabla\phi$) along a closed contour surrounding each defect (1). Crucially, this integration is only valid along paths with continuous phase and must not cross phase discontinuities, which are inherently present within reentry cores.

$$I = \frac{1}{2\pi} \oint_C \nabla\phi \cdot d\vec{l} \tag{1}$$

To determine if a region is discontinuous, we introduce a case-specific threshold based on local phase gradients to identify regions with rapid phase changes between neighboring points. This approach highlights discontinuous regions corresponding to anatomical structures (e.g., veins, valves, scar tissue) or functional features such as lines of block or rotor cores. We applied the algorithm to 69 clinical left atrial AT cases mapped using the CARTO system, excluding bi-atrial ATs and ATs driven by accessory pathways. Ground truth reentry circuits were annotated in collaboration with electrophysiologists and used for validation.
Results: The algorithm correctly identified both reentry circuits in 65 of 69 cases (94.2%), based on agreement with annotated circuit locations. Failures occurred in cases with extensive scarring, where even expert electrophysiologists struggled to determine the diagnosis, sometimes only doing so post hoc.
Conclusion: Reentry circuits in left atrial AT can be accurately detected by automatically computing topological charges around phase defects under continuity constraints. Performance decreases in highly complex cases where LAT and phase maps do not fully capture the arrhythmia dynamics.