# Analysis of Cardiac Fibrillation Using Phase Mapping

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**KEYWORDS**

• Cardiac arrhythmia • Ventricular fibrillation • Atrial fibrillation • Mapping • Reentry • Phase analysis

**KEY POINTS**

- Phase mapping provides a way to represent the electrical activation–recovery cycle of cardiac tissue and can be used for the robust identification of reentry.
- The calculation of phase angle involves several processing steps, which must be implemented carefully to obtain a good estimate of phase.
- Preprocessing of electrograms, especially those recorded from the atrium, is important to obtain a robust estimate of phase angle.

## INTRODUCTION

Although the detailed mechanisms that sustain fibrillation in the human heart continue to be debated,[1–3] it is well accepted that the irregular waveform seen on a surface electrocardiogram during atrial (AF) and ventricular (VF) fibrillation arises from an irregular and constantly changing activation sequence. Electrical activity in the myocardium during fibrillation can be mapped with electrode arrays in the in situ heart[4–6] using voltage-sensitive fluorescent dyes in the isolated heart.[7–9] Recent studies indicate the potential utility of body surface electrodes for mapping atrial activity.[10,11] All of these modalities show complex and often irregular activity. Interpreting these signals is difficult, and this is an obstacle both to understanding the basic science underlying these clinically important arrhythmias and to developing strategies for clinical interventions, such as atrial ablation.

The idea of using phase to represent electrical activation and recovery in the heart was developed in the 1980s, with a focus on identifying the timing of abnormal beats capable of initiating reentry.[12] These ideas were then extended to identify functional reentry during fibrillation from singularities in phase maps[13] obtained from optical mapping with voltage-sensitive fluorescent dyes. This approach had the important advantage that it was not necessary to construct maps of activation times, as in earlier studies of arrhythmia mechanisms,[14] which can be difficult in areas of block and slow conduction.

The focus of this review is to explain the benefits and limitations of phase mapping for both basic science and clinical applications by describing the concepts of phase analysis and methods for obtaining phase from voltage measurements, as well as the potential hazards associated with different approaches. There is a focus on applications in the human heart, and the aim is to complement other recent reviews that concentrate on interpolation and phase mapping,[15] and phase analysis in simulations.[16]

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## MECHANISMS OF REENTRY AND FIBRILLATION IN THE HEART

Reentry describes a circulating wave of electrical activation that continually propagates into recovering tissue, resulting in rapid and self-sustaining electrical activity.[3] Reentry is an important mechanism in both AF and VF.

During reentry, activation rotates around a core, which may be an anatomic obstacle or a region of functional block. The center of rotation is surrounded by tissue in all parts of the activation–recovery cycle. In the thick-walled ventricles, the center of rotation is a filament around which the activation wavefront is wrapped as a scroll wave. If the filament is aligned across the ventricular wall, then it is observed as a center of rotation, or rotor, on the ventricular epicardium. However, other filament configurations are possible, and these include ring-shaped filaments that give rise to spreading circular activation waves on the epicardial surface.[16] The more complex anatomy of the thin-walled atria offers more opportunities for anatomic reentry. Atrial filaments are comparatively short, and so the centers of rotation effectively behave as points rather than filaments.

In early studies that provided direct evidence of reentry, activation times derived from unipolar electrograms obtained with contact electrodes were used to determine the progression of an activation wave around a reentrant circuit.[17–19] Subsequent studies of tortuous activation sequences during VF also used this approach,[20] but beyond illustrative examples it was difficult to quantitatively describe the reentrant mechanism.

The advent of cardiac mapping based on signals from voltage-sensitive fluorescent dyes offered a way to image electrical activation of the myocardial surface with much greater spatial resolution,[21,22] and this has now become a standard technique in the experimental setting. Phase analysis was developed to interpret the high spatial resolution information that can be gained from these measurements,[13] and offers an alternative way to detect and quantify reentry than approaches based on activation times. The fluorescent dyes used in optical mapping experiments are toxic, and so cannot be used in the in situ human heart. As a result, the approaches developed for transforming optical action potentials into phase have been adapted for use with electrograms.[5,15]

## BASIC PRINCIPLES OF PHASE ANALYSIS

The idea of using phase to represent a repetitive or oscillatory process is commonly used in the study of other physical systems, where the state of the system is represented as a phase angle. In the example shown in **Fig. 1**, the behavior of a simple

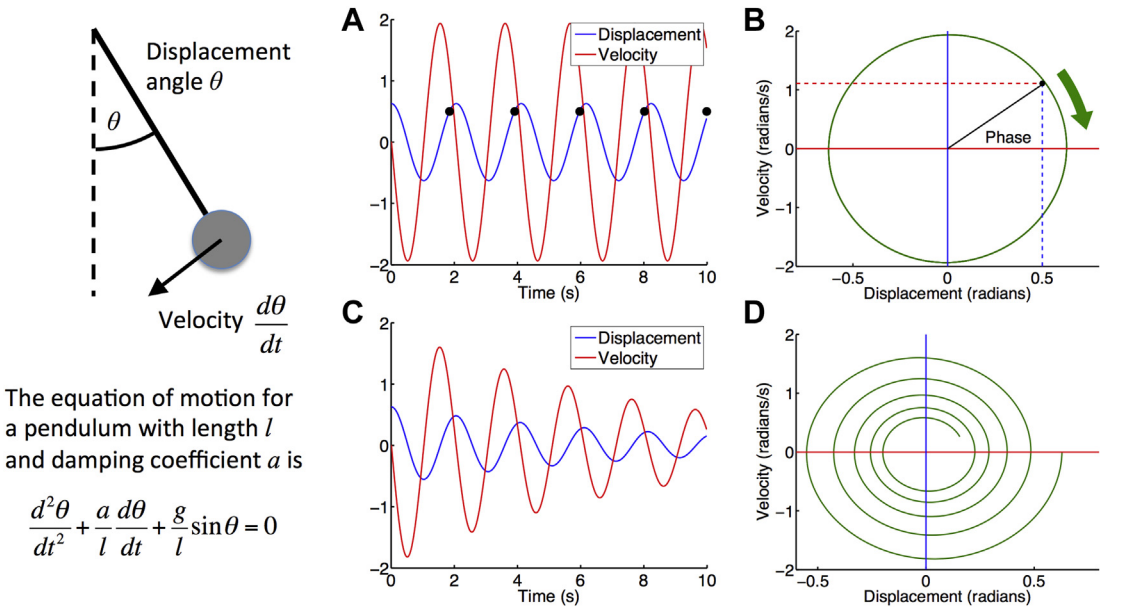


**Fig. 1.** Motion of a simple pendulum with and without damping described using the equation shown. (*A*) Time series plot of displacement (*blue*) in radians, and velocity (*red*) in radians $s^{-1}$ for an undamped pendulum of length 1 m, with initial displacement of $\pi/5$ radians. (*B*) State-space plot of velocity plotted against displacement, where red and blue lines show zero velocity and zero displacement, respectively. Red and blue dashed lines indicate point in the pendulum oscillations where displacement is 0.5 radians. These points are shown for each cycle in *A*. (*C*, *D*) corresponding plots for a damped pendulum.