Minimum Time Duration for Detecting Phase Singularities in Human Persistent Atrial Fibrillation

Shamsu Idris Abdullahi[1*], Noor Qaqos[1], Ekenedirichukwu N Obianom [2], Fan Feng [1], Abdulhamed M Jasim[1], G André Ng[2,3], Xin Li[1,3]

[1]School of Engineering, University of Leicester, Leicester, UK
[2]Department of Cardiovascular Sciences, University of Leicester, Leicester, UK
[3]National Institute for Health Research Leicester Cardiovascular Biomedical Research Centre, UK

Abstract

Atrial fibrillation (AF) is a leading cause of cardiovascular morbidity, affecting millions globally, Phase singularity density maps play a crucial role in cardiac electrophysiology by identifying arrhythmogenic substrates. However, the ideal duration for capturing reliable phase singularity data remains uncertain. This study examines the correlation between phase singularity density maps generated from different durations and a 3-minute gold standard. Electrophysiological data from 10 patients were analyzed using MATLAB, with maps computed for time frames ranging from 5 to 180 seconds. The results show a strong correlation (average coefficient > 0.9) for durations longer than 90 seconds, indicating that shorter acquisition times may be sufficient for accurate analysis. These findings could help optimize clinical workflows in cardiac electrophysiology.

1. Introduction

Atrial fibrillation (AF) is the most common cardiac arrhythmia encountered in clinical practice, affecting 1-2% of the general population[1]. Phase mapping and rotor-based driver detection have become central methods in elucidating atrial fibrillation (AF) mechanisms discussed challenges in reconstructing instantaneous phase from unipolar atrial contact electrograms due to complex signal morphologies such as uniphasic or biphasic deflections, varying R vs S-wave dominance, and noise[2]. They proposed a preprocessing step consisting of sinusoidal recomposition (weighting waveform components by the negative slope) prior to applying the Hilbert transform and demonstrated that this improves the accuracy of phase estimation, particularly aligning phase zero-crossings with local activation times[3]. Narayan et al. (2012) introduced the CONFIRM (Conventional Ablation with or Without Focal Impulse and Rotor Modulation) trial, in which localized electrical rotors and focal impulses were identified in 98 of 101 patients with sustained AF. Their results showed that targeting these sources with ablation (FIRM-guided) resulted in significantly higher acute termination or slowing of AF and better long-term freedom from AF compared to conventional ablation alone[4]. Cardiac arrhythmias like atrial fibrillation involve intricate electrophysiological processes, including phase singularities. These singularities indicate rotational activations in cardiac tissue and serve as crucial markers for detecting arrhythmogenic substrates[5]. Accurate identification and analysis of phase singularities are vital for guiding ablation therapy and enhancing patient outcomes. Although phase singularity density maps are commonly used in both research and clinical practice, the ideal duration for acquiring reliable data remains unclear[6]. Extended data collection may be impractical in clinical settings, highlighting the need to balance data quality with acquisition efficiency[7]. This study investigates the relationship between phase singularity density maps generated from shorter time frames and a 3-minute gold standard, aiming to determine the shortest duration needed for reliable analysis. A gold standard is the initial 180 seconds of data which was utilized.

2. Materials and Methods

2.1. Electrophysiological Study

Our study comprised ten patients with persistent atrial fibrillation (persAF) who were receiving their initial left atrial (LA) catheter ablation procedure[1]. To direct the ablation procedure towards the rotors, we obtained up to 300 seconds of noncontact electrogram (EGM) data from the left atrium (LA) using the (Ensite Array system from St Jude Medical). The generated data was then analysed using the Matlab software. As stated before, phase density zones were identified in the LA. 40% of the patients had their atrial fibrillation (AF) terminated, with

30% experiencing atrial flutter and 10% returning to normal sinus rhythm, by rotor ablation before undergoing pulmonary vein isolation (PVI). All 10 patients experienced no negative outcomes[8].

Table 1. Clinical Characteristics of the Patients

	Median	Min.	Max.
Male (n)	10	-	-
On amiodarone (n)	2	-	-
Age (years)	57.8	36.1	76.4
Days in AF pre-procedure	219	132	848

2.2. AF EGM Pre-Processing

We examined 2048-channel virtual EGMs (EnSite Array, Abbott; 5 min). The electrocardiogram (EGM) recordings, which lasted for 5 minutes, were initially sampled at a rate of 2034.5 Hz[2]. To reduce processing time and storage requirements, the recordings were subsequently re-sampled to a rate of 512 Hz using the cubic interpolation method. To improve the accuracy of rotor identification, we conducted QRST subtraction, because ventricular far field activity in EGMs can occasionally be misleading, showing up as frequency components within the atrial frequency spectrum, affecting PS identification accuracy, therefore QRST subtraction was conducted[1].

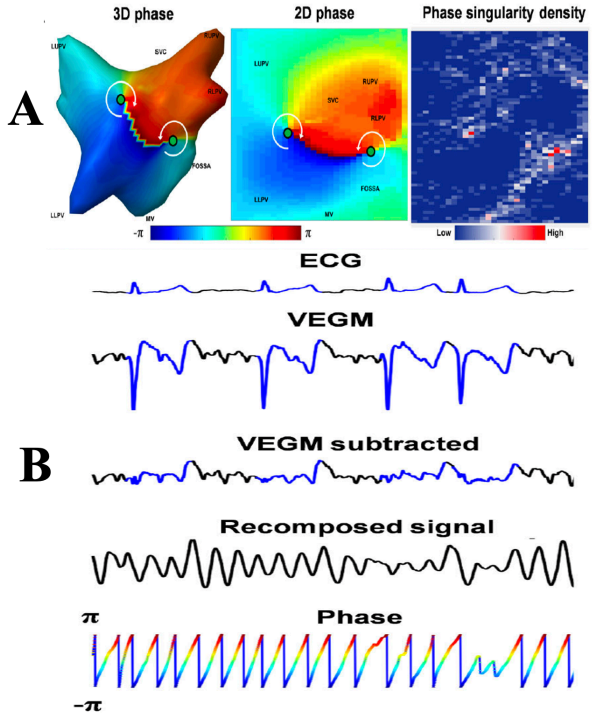

Figure 1. Data acquisition and signal processing. (A) Reconstructed 3D left atrial geometry with color-coded phase map, its 2D representation (cylinder projection) showing PS points (green circles) and example of a 2D PSD map. (B) Example of ECG, VEGM, QRST-subtracted VEGM, recomposed signal using sinusoidal wavelet reconstruction and Phase signal[9].

2.3. Generating Phase Mapping

The figure 1 above shows that the ventricular QRST complex in the surface ECG (red trace) contaminates atrial EGMs (yellow). The QRST subtraction method removes this ventricular far-field signal, leaving a cleaner atrial electrogram (blue). Mathematically, this can be model as:

$$EGM_{\text{sub}}(t) = EGM_{\text{raw}}(t) - Q\hat{R}ST(t) \quad (1)$$

where $Q\hat{R}ST(t)$ is an estimated QRST template obtained from averaged ECG cycles or principal-component reconstruction aligned to the R-wave timing.

2.4. Band-Pass filtering

The atrial component is then band-pass filtered $EGM_f(t) = \text{BandPass}\{EGM_{\text{sub}}(t)\}$ [10].

2.5. Hilbert Transform (instantaneous phase)

The analytic signal is computed using the Hilbert transform [11],

$$z(t) = EGM_f(t) + j\,\mathcal{H}\{EGM_f(t)\} \quad (2)$$

where $\mathcal{H}\{\cdot\}$ is the Hilbert operator. The instantaneous phase is then:

$$\phi(t) = arg\,[z(t)] \quad (3)$$

giving a continuous phase that wraps between $-\pi$ and $+\pi$

2.6. Mathematical Model of the Phase Singularity Density Map

Let: $PS(x, y, t) = 1$, if a PS is present at coordinates (x, y) and time t, otherwise 0. T= total number of sampled time frames. Then, the Phase Singularity Density Map (PSDM) is defined as the temporal average of PS presence at each spatial location [9]

$$D(x,y) = \frac{1}{T}\sum_{t=1}^{T} PS(x,y,t) \quad (4)$$

or equivalently, $D(x,y) = \Pr[PS(x,y,t) = 1]$. Thus $D(x,y) \in [0, 1]$ represents the fraction of time (or probability) that a phase singularity occurs at electrode (x,y). Pr stands for Probability which is shorthand for the probability that something happens. In this equation $\Pr[PS(x,y,t) = 1]$ means that the probability that a phase singularity (PS) occurs at location (x,y)at any random time t.

3. Results

The density map for each shorter duration was compared to the three-minute baseline map for individual patients.

For each time interval, phase singularities were identified and mapped, potentially highlighting regions of interest, such as sources of atrial fibrillation.

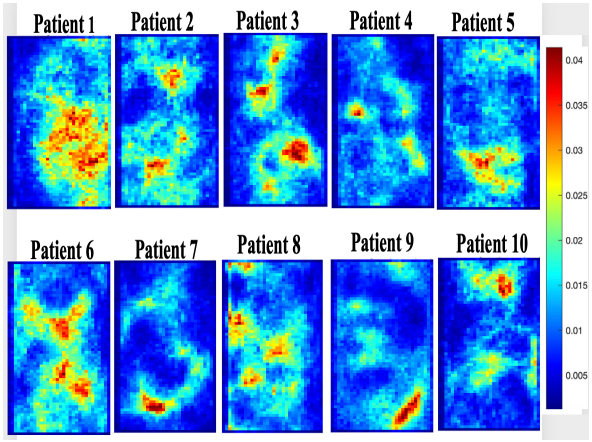

Figure 2. Phase Singularity density maps for all the 10 patients (for 3 mins each)

After evaluating each patient separately, the average correlation for each time duration was computed across all patients to identify overall patterns. The correlation between phase singularity density maps and the gold standard improved as duration increased, stabilizing around 120 seconds. For durations longer than 90 seconds, the average correlation coefficient across patients reached 0.91.

Figure 3 illustrates the phase singularity density maps computed for patient 9 using atrial electrogram recordings at different time durations, increasing in 10-second intervals from 10s to 180s. The colour scale quantifies the normalized probability of observing a phase singularity (PS) at each spatial coordinate on the left atrial geometry. Regions shaded in warmer colours (red to yellow) represent areas of higher PS occurrence, The results show that the map obtained at 90 seconds closely resembles that at 180 seconds, indicating that a 90 second recording duration is sufficient to capture stable phase singularity distributions without the need for extended acquisition.

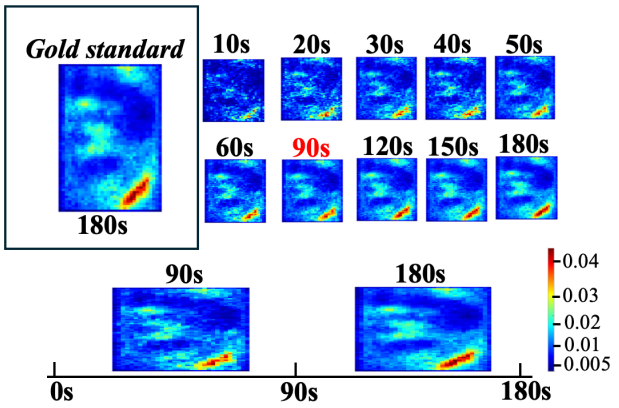

Figure 3. Number of Phase Singularity per frame of a patient.

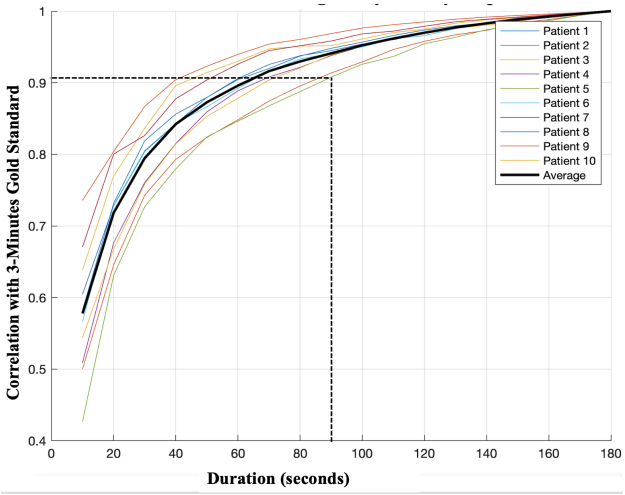

Figure 4. Correlation of Phase Singularity Density Maps

From figure 4, The Results illustrates the relationship between observation duration and correlation with a gold standard as well as the average of the correlation between the 10 patients. The black line, indicating the average correlation, shows that for most patients, durations of approximately 90 seconds or longer yield a strong correlation of over 0.9 with the 3-minute reference standard.

In this result, it indicates that phase singularity density maps derived from shorter durations (≥ 90 seconds) maintain a strong correlation with the reference 3-minute gold standard map. This finding implies that meaningful and reproducible spatial patterns of atrial activity can be captured using substantially shorter data segments,

reducing computational load without compromising accuracy.

4. Discussion and Conclusions

Although the correlation increases with duration for all patients, there is clear variation in how quickly everyone's correlation levels off. In the results, most patients achieve a correlation of 0.9 with the gold standard sooner than others, suggesting person-specific differences in phase singularity patterns or signal characteristics. This implies that accurate phase singularity analysis can be achieved with much shorter data collection periods, which is particularly beneficial in time-sensitive clinical environments. Previous studies have confirmed the reliable detection of phase singularities in shorter datasets, aligning with our results[1]. However, our study builds on this by quantifying the correlation between shorter durations and the gold standard, offering a stronger foundation for clinical decision-making.

This study shows that shorter data collection periods for around 90 seconds or more might be nearly as reliable as 3-minute recordings for accurate phase singularity analysis, potentially improving efficiency in clinical cardiac electrophysiology. Differences between patients suggest that a fixed duration may not be suitable for everyone, as some individuals might need extended monitoring to obtain dependable results. For most patients, the correlation appears to level off around 90 seconds, suggesting that extending observation beyond this point offers minimal additional benefit. Future research should confirm these findings in larger and more diverse patient groups.

Acknowledgments

This work was funded by The Petroleum Trust Development fund (PTDF) Nigeria, (PTDF Ref. No**.** PTDF/ED/OSS/PHD/SIA/1856/2)

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Address for correspondence:

Shamsu Idris Abdullahi,
University of Leicester, Leicester, UK,
sia15@leicester.ac.uk