Fast and Robust P Wave Alignment Using Area-Based Comparison

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Abstract

The precise alignment of P waves in surface ECGs is crucial for analyzing beat-to-beat atrial depolarization but remains difficult due to their low amplitude, slow dynamics, and unclear boundaries. Traditional cross-correlation (CC) methods may not reliably reflect true similarity, especially in poor-quality signals. We investigated a morphology-based alignment approach called Two-Window Minimization (TWM) and compared it with standard CC alignment. Two new TWM variants using trapezoidal and integral segment integration were proposed, and the effects of window size and position were systematically evaluated. The method was tested on surface ECGs from 47 pediatric patients in sinus rhythm, using intracardiac electrograms as ground truth. Accuracy was assessed by comparing ECG-based alignment with atrial activation timing in coronary sinus electrograms. The basic TWM was the least time-consuming (1.03 s per dataset). The integral-based TWM achieved the lowest mean alignment error (0.06 ms), while the trapezoidal-based version showed the least variability (SD = 3.08 ms). CC performed well only at large window sizes (–0.15 ± 3.55 ms), but degraded with shorter segments. Overall, the trapezoidal TWM provided the best balance of precision, robustness, and speed, making it well suited for real-time or embedded applications.

1. Introduction

Automatic analysis of the P waves is essential for meaningful morphological and electrophysiological assessment, ensuring that the aligned segments reflect homologous atrial activations. P wave morphology carries information about the underlying atrial substrate and may reflect electro-anatomical remodeling, which highlights the clinical relevance of accurate alignment. Even minor temporal misalignments can introduce errors into subsequent analyses and potentially influence clinical decisions [1, 2].

In contrast to the alignment of the QRS complex, aligning the P wave presents unique challenges due to slower atrial depolarization, lower frequency content, and weaker atrial potentials [3]. Moreover, the lack of distinct onset and offset markers complicates precise delineation. Cross-correlation (CC) is commonly used in practice [4], but may produce misleading results when P wave amplitude profiles differ significantly. This study investigates an alternative based on the Two-Window Minimization (TWM) method [5], which assesses morphological similarity by comparing the area under the ascending and descending phases of the P wave. We extend the TWM framework by adjusting parameters and proposing metrics tailored to the atrial morphology. The aim is to develop a more robust and physiologically meaningful alignment metric, improving the accuracy and interpretability of atrial electrophysiological analyses. Beat-to-beat variability in P wave morphology can indicate unstable atrial activation in remodeled atria, further supporting the need for precise alignment. Such robust alignment is particularly beneficial in signal averaging applications, where multiple atrial cycles must be accurately synchronized to enhance signal quality and uncover subtle features [6].

2. Methods

2.1. Data

We analyzed data from 47 pediatric patients from a publicly available database [7], selecting records with normal sinus rhythm to ensure consistent P waves. The advantage of this database is the availability of intracardiac electrograms, which served as the ground truth for atrial depolarization timing. We assumed that atrial depolarization follows a consistent propagation pattern, maintaining stable temporal synchronization between intracardiac activity and the surface P wave for each patient. Figure 1 illustrates the peak positions of the P wave and the corresponding atrial activation time.

The surface ECG analysis was performed on lead V6, as it exhibited the most consistent and unimodal P wave morphology across subjects in our dataset. While the algorithm is in principle applicable to any lead with a clear P wave shape — such as lead II — and could be adapted to handle biphasic morphologies (e.g., in lead V1), we selected ECG lead V6 based on its superior signal quality and morphological stability in our recordings. This choice ensured detection of atrial activity in the context of our method and dataset.

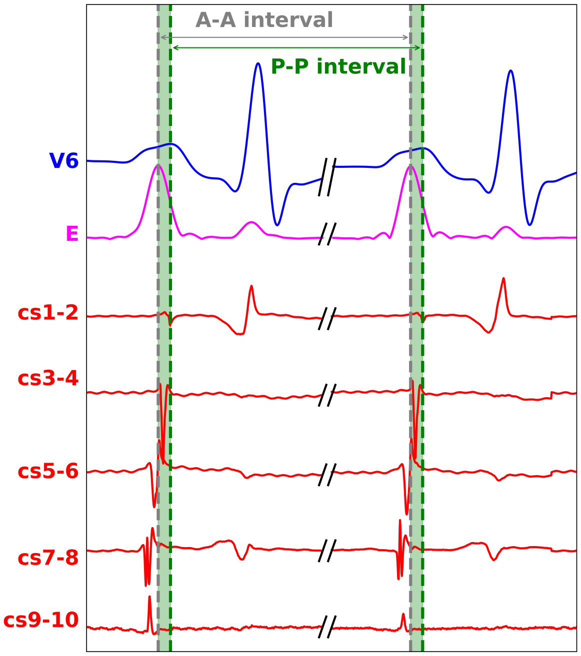

Figure 1. An illustrative example of the dataset. The coronary sinus (CS) intracardiac signals are displayed in red, while the envelope (E) of the summed CS leads is displayed in magenta. It is assumed that the position of the P wave peak and the corresponding atrial activation remain stable within a single patient. The PP and AA intervals are highlighted to demonstrate this temporal correspondence.

2.2. Two Windows Minimization

The Two Window Minimization (TWM) method evaluates the morphological similarity between P waves by minimizing the area difference between two specific segments: the ascending and descending slopes. These segments reflect different phases of atrial activation.

The TWM algorithm, introduced in [5], uses rectangular windows to approximate the morphology of these segments. The metric is computed in two phases, as follows:

Pre-running phase: Two rectangular windows are defined on a reference waveform (typically an averaged template). The first window represents the ascending slope and the second the descending slope. Let:

- H_{r1}, W_{r1} be the height and width of the first rectangle,
- H_{r2}, W_{r2} be the height and width of the second rectangle,
- $\Delta A_r = H_{r1} \cdot W_{r1} - H_{r2} \cdot W_{r2}$ be the area difference between the reference rectangles.

Running phase: The same windows (with fixed positions and widths) are moved over the incoming signal (P wave). For each shift, we compute the following.

- H_{n1}, W_{n1} and H_{n2}, W_{n2} — the heights and widths of the rectangles on the incoming P wave,
- $\Delta A_n = H_{n1} \cdot W_{n1} - H_{n2} \cdot W_{n2}$ — the area difference between the rectangles on the incoming segments.

An alignment deviation (AD) is defined as

$$AD = |\Delta A_r - \Delta A_n|$$

Optimal alignment minimizes AD.

2.3. Experimental Design

In this study, P waves were analyzed on a beat-to-beat basis. They were detected using a wavelet transform, and beats with atypical morphologies were excluded. The P waves were aligned using the proposed morphological metrics, and the corresponding activation time was identified as the peak of the envelope of the intracardiac CS electrograms. The temporal difference (Δt) between the intracardiac activations was then computed and used as a measure of alignment error. An illustrative example of this process is shown in Figure 2.

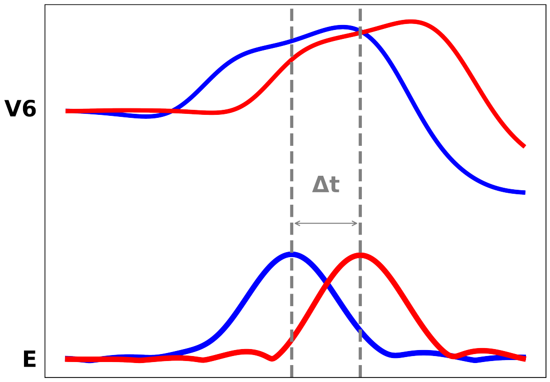

Figure 2. Illustration of the alignment error estimation process. Two consecutive P waves (red and blue) are aligned based on surface ECG. Atrial activations are derived from the envelope of summed intracardiac signals. The time difference Δt represents the alignment error.

2.3.1. Window Width

To identify the most informative segments of the P wave, we analyze windows centered around fixed intra-wave landmarks within a 100 ms duration, around the P wave peak. Two temporal anchors are defined at the 25th and 75th percentiles of this window (q25 and q75), corresponding to the early and late portions of the P wave.

Around each anchor, we construct symmetric windows of varying widths (see in Fig. 3), expressed as percentages of the total duration of the P wave template (e.g. 10%, 20%,..., 100%), with each window pair split equally between q25 and q75. These windows serve as regions of interest for computing signal metrics.

This design enables systematic comparison of different temporal segments within a single patient, regardless of intersubject variability, to determine which regions provide the most relevant analytical information.

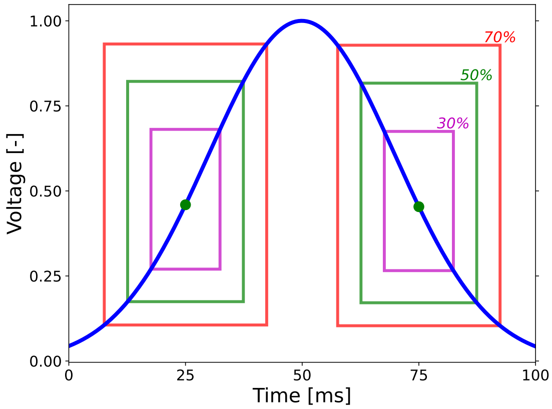

Figure 3. Illustration of the experimental design. A P wave template is shown with two time windows symmetrically placed around the 25% and 75% time points of the P wave duration (assumed to be 100 ms). Different window widths (e.g., 30%, 50%, 70%) were tested to evaluate the aligning performance within these regions.

2.3.2. Metric Modification

Although the method [5] uses the area of a simple rectangle, we explore alternative approaches based on the integration of the actual waveform within each window. Specifically, we compare two variants: (i) a trapezoidal approximation using only the first and last points of the window (TWM_T) and (ii) continuous integration using all available data points within the window (TWM_I). These approaches capture more accurately the local morphology of the P wave and may be more sensitive to subtle changes in signal shape within the selected regions.

3. Results

The results presented in Table 1 reveal several key insights into the performance of the aligning methods evaluated. The TWM_I consistently achieved the lowest absolute mean error in all window widths of signal coverage, indicating a higher accuracy of alignment. Furthermore, TWM_T showed the lowest variability, as reflected by its standard deviation values, suggesting robust performance even under challenging conditions.

Table 1. Alignment error ($\mu \pm \sigma$ in ms) for each method across different window widths. Lower values indicate better performance.

Method	70 %	50 %	30 %
TWM	-1.85±9.40	-2.95±9.19	-2.83±8.60
TWM_I	-0.06±5.36	-0.13±5.18	-0.24±5.33
TWM_T	0.41±3.26	0.17±3.10	**0.05±3.08**
CC	-0.15±3.55	-0.13±4.55	-0.26±5.81

At high temporal coverage (wide windows), CC performed comparably well, exhibiting relatively low error and variability. However, its performance deteriorated at lower coverage levels, where both error magnitude and variability increased. This highlights the advantage of morphology-based alignment approaches, such as TWM, particularly in cases of atrial remodeling, where the P wave can exhibit low amplitude and fractionation, conditions commonly associated with atrial fibrillation and ablation failure.

We report the 5th to 95th percentile range $[p_{05}, p_{95}]$ alongside the mean and standard deviation to better characterize alignment error variability while reducing the impact of outliers (see Table 2).

Table 2. Inter-percentile [p_{05}, p_{95} in ms] alignment error are shown across different window width for each method. Smaller values and tighter intervals signify superior performance.

Method	70 %	50 %	30 %
TWM	[-18.0, 15.0]	[-18.5, 13.5]	[-18.5, 13.0]
TWM_I	[-8.0, 7.0]	[-8.0, 6.5]	[-9.0, 7.5]
TWM_T	**[-4.0, 5.0]**	**[-3.0, 3.0]**	**[-4.0, 3.5]**
CC	**[-5.0, 4.0]**	[-6.0, 5.0]	[-7.5, 5.5]

Table 3 shows the computational efficiency of the alignment methods. The original TWM is fast, but lacks precision. As expected, TWM_I is slower due to additional operations. CC takes the longest time due to its more complex multistep process. In particular, TWM_T achieves a remarkably fast runtime while maintaining high alignment accuracy, clearly outperforming the other methods in terms of speed–accuracy trade-off. This makes it particularly suitable for time-sensitive or real-time applications.

Table 3. Total processing time (seconds) required for each alignment method to analyze the entire dataset (611 P waves). Shorter durations indicate more computationally efficient implementations. (Intel(R) Core(TM) i7-7500U CPU @ 2.90 GHz, RAM: 32 GB, Python 3.12.2.

Method	70 %	50 %	30 %
TWM	**01.13**	**01.07**	**01.03**
TWM_I	07.87	07.59	07.62
TWM_T	01.45	01.38	01.55
CC	36.44	37.23	27.33

4. Discussion

The evaluation of alignment methods revealed important trade-offs between computational efficiency and accuracy. The original TWM method, while fast, showed limited precision, making it unsuitable for high-accuracy tasks. The TWM_I, although more precise, required significantly more processing time due to additional computations. Although accurate, CC was the slowest because of its multistep process that involved shifting, interpolation, and windowing. TWM_T emerged as the best compromise, offering a balance between speed and accuracy, crucial for applications requiring real-time processing, such as in an electrophysiology laboratory.

These findings suggest that method selection should be driven by specific needs, where fast methods are preferable for less demanding applications, while accurate ones can be used when precision is the primary concern such as for the analysis of beat-to-beat variability of the P wave as a marker of electro-anatomical remodeling.

This study was purposely carried out in a pediatric cohort, in which atrial tissue is assumed to be structurally intact and free of the remodeling changes commonly seen in adults. As such, the results reflect the alignment performance under relatively ideal physiological conditions. Future work will focus on adult patients, where factors such as atrial fibrosis and conduction abnormalities can pose additional challenges for signal alignment.

5. Conclusion

The TWM_T method offers the best potential for real-time applications that combine efficiency and precision. Future work should explore further optimization of TWM and its variants to reduce processing times while maintaining alignment quality. Expanding the evaluation to larger datasets and real-world scenarios will provide deeper insights into the scalability and robustness of these methods.

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