Improving Atrial Cardiomyopathy Diagnosis Through High Precordial Electrode Placement: An in silico Study

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Abstract

Atrial cardiomyopathy (AtCM) is associated with new-onset atrial fibrillation, arrhythmia recurrence after pulmonary vein isolation, and ischemic stroke. The amplified P-wave duration (APWD) as surrogate marker for invasively measured atrial activation time offers a promising non-invasive, cost-effective tool to diagnose AtCM. However, despite high sensitivity and specificity, APWD remains limited in clinical practice due to challenging P-wave offset detection in some patients. We hypothesize that electrodes closer to the atria yield P-waves with early on-, late offset and clearer delineation, enabling APWD measurement more accurately compared to the conventional 12-lead ECG. Therefore, body surface potential maps were simulated using 100 atrial and 25 torso geometries derived from statistical shape models, combined with 21 fibrosis distributions derived from electroanatomical voltage mapping. Unipolar setups (right-leg and Wilson's central terminal references) were optimized by identifying anterior and posterior positions with high P-wave amplitude and clearly defined early on- and late offsets. The optimized positions were located above the conventional V1/V2 electrodes and align with previous studies to improve standard P-wave recording. In conclusion, this work demonstrates that optimized electrode placement could improve APWD measurement, thereby enhancing AtCM diagnosis.

1. Introduction

Atrial cardiomyopathy (AtCM) is associated with new-onset atrial fibrillation (AF), arrhythmia recurrence after pulmonary vein isolation (PVI), and an increased risk for ischemic stroke [1, 2]. To diagnose and quantify AtCM in vivo, electroanatomic mapping (EAM) and late gadolinium enhancement magnetic resonance imaging (LGE-MRI) are used but limited due to invasiveness, required expertise, and availability [1, 2]. The amplified P-wave duration (APWD) as surrogate for the invasive atrial activation time (IAAT) is based on the 12-lead electrocardiogram (ECG) with adjusted sweep speed (175 mm/s) and amplification (80 mm/mV) and provides a promising alternative that is non-invasive, cost-effective, easily available, and can be standardized [3, 4]. However, APWD is not yet established to diagnose AtCM. Currently, its use, despite high sensitivity and specificity, remains limited in clinical practice due to challenging APWD measurements for certain patients, potentially leading to marked inter- or intraobserver variability. To measure APWD, P-waves with clear delineation of on- and offset using all 12 ECG-leads are required. Therefore, optimized lead placement and fewer needed leads could improve APWD measurement in clinical practice. We hypothesize that electrodes closer to the atria enable APWD measurement more accurately compared to the conventional 12-lead ECG.

2. Methods

2.1. In silico Body Surface Potential Maps

A virtual patient cohort was created using 100 publicly available atrial models and 25 torso geometries derived from statistical shape models (SSMs) [5, 6]. Additionally, high-density bi-atrial EAMs in sinus rhythm (36 patients, 86 % male) were provided by the University Heart Center Freiburg-Bad Krozingen [7]. All patients provided written informed consent and had symptomatic persistent AF. EAMs were recorded prior to first PVI and low-voltage areas (LVAs) were defined by a bipolar voltage threshold of 0.5 mV. To model AtCM, 21 LVA distributions with at least 10 % LVAs in one of the atria were first mapped to the mean atrial mesh as proposed previously [8] and subsequently mapped to the individual geometries. In total, this yielded 53 116 feasible combinations of which 2 421 represented healthy individuals, and 50 695 represented AtCM.

Electrical propagation in the atria was simulated using the diffusion reaction eikonal alternant model with openCARP [9, 10]. Ion channel conductances of the Courtemanche et al. model [11] and tissue conductivities were regionally adjusted [12], and additionally remodeled for AtCM [13]. To account for structural and electrical re-

modeling in AtCM, percolation with 50 % non-conductive and 50 % slow conductive elements was applied in the LVAs [14]. In the latter, longitudinal conduction velocity was reduced by 50 %, anisotropy ratio was increased to 2.5, and ionic conductances were adjusted to account for TGF-β1 remodeling [15]. Body surface potential maps (BSPMs) of atrial depolarization were obtained by means of the boundary element method [16] and referenced to the right leg (RL) and Wilson's central terminal (WCT).

2.2. Optimizing Electrode Placement

The optimal position to measure APWD is the one with APWD closest to IAAT [3]. As the APWD could not be measured directly in silico due to dataset size prohibiting manual annotation and the lack of automated methods beyond 12-lead analysis [17], 12 surrogate features were defined to analyze P-wave signal quality instead. These features follow the heuristic that positions characterized by an early on- and late offset should reflect IAAT most accurately. Thus, feature analysis was performed over the first, and last, $5, 10, 15, 20$ ms w.r.t minimum, respectively maximum, atrial activation time. To ensure reliable APWD measurement at the optimized position, high signal amplitude at the P-wave beginning and end was favored by analyzing the P-wave area and the RMS voltage, while clear delineation was favored by the maximum absolute gradient. All features were normalized to $[0, 1]$ and summed up to a global feature value $[0, 12]$. For the analysis, BSPM signals were aligned to the isoelectric line w.r.t the on- and offset, respectively. The best position across multiple models was then determined by maximizing the median of the global feature value. Additionally, to determine the best position across multiple torso models based on the global feature value, the anterior and posterior torso surfaces were divided into 100 distinct regions using 10 equally spaced sections in superior-inferior and lateral directions. Each region covered approximately the size of an ECG electrode. Electrode positions were analyzed separately for healthy and AtCM, anterior and posterior, on- and offset, and for each reference electrode. To assess the potential for approximating the optimized position by routine leads, linear coefficients to reconstruct the signals at the offset-optimized position for AtCM with the standard 12-lead ECG (I,II,V1-V6) were derived across all models [18].

3. Results

For all setups, the optimized positions were located superior to the conventional V1/V2 electrodes. Using the RL reference, most models had high individual feature values and a high global feature value in the middle of the anterior chest. Consequently, also a high median global feature value across all 100 atrial models was found in the respective region (Figure 1). The area with highest global feature values was homogeneous, clearly spatially defined and spread over more than 4 adjacent regions of the 100 segment torso model. Small differences in extension and location could be observed for different torso models, where typically models with larger chest and abdominal diameter yielded more elliptical patterns (right columns in Figure 1), while smaller diameters had more elongated and less symmetrical regions with high median global feature values. For WCT reference, the largest global feature values were found in the same region with lower values compared to the RL reference. Additionally, high median global feature values were found in the inferior torso and posteriorly on the left lateral chest for WCT reference. In the region-based analysis across all models, high median global feature values were observed in the anterior chest irrespective of the setup (Figure 2). For the RL reference, the best region was located slightly to the right and superior for the onset compared to the offset. While the same optimized region was found for the onset in both AtCM and healthy models with median global feature values of 9.1 and 9.2, for the offset, the region was larger, located more to the left

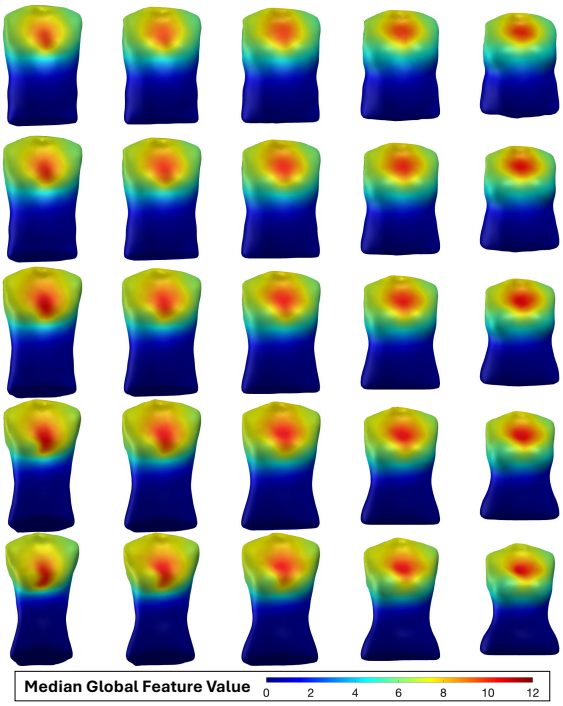
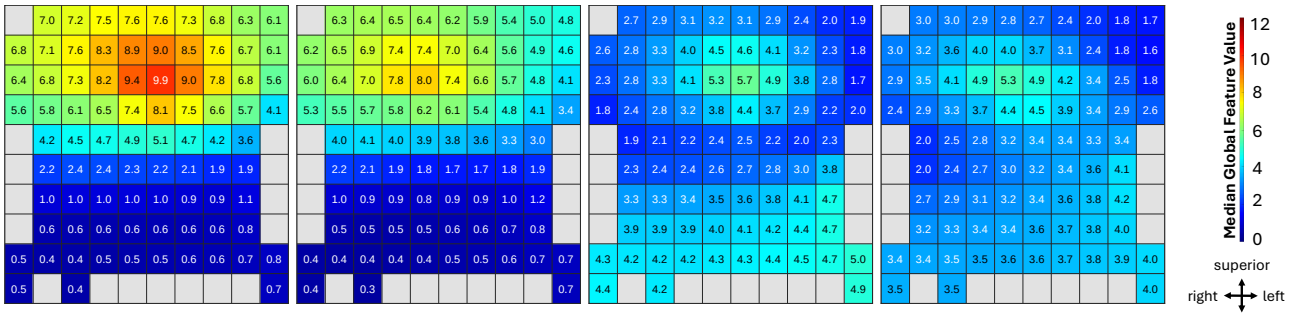


Figure 1: Median global feature values across all healthy atrial models for the P-wave offset, right leg reference, anterior view. High median global feature values, indicating a position with clear P-wave offset, are visualized in red. Torso models are ordered by coefficients of the two first eigenmodes with decreasing abdominal diameter from top to bottom and increasing chest diameter from left to right.



(a) Healthy, RL reference (b) AtCM, RL reference (c) Healthy, WCT reference (d) AtCM, WCT reference

Figure 2: Median global feature values for P-wave offset on the anterior torso. Gray regions were missing in some torso models and excluded from the analysis. RL: Right leg, WCT: Wilson's central terminal, AtCM: Atrial cardiomyopathy.

and had higher values (9.9 vs. 8.0) in healthy models compared to models with AtCM (Figure 2). For the WCT reference, anteriorly the same regions in the superior-medial chest yielded high median global feature values. However, overall lower median global feature values were observed with a maximum of 8.0 for the onset in both setups, and 5.7 in healthy and 5.3 in AtCM models for the offset (Figure 2). Signals at offset-optimized positions for AtCM are visualized in Figure 3. Linear coefficients for leads I, II, and V1-V6 for the best offset positions in AtCM models were 0.80, -1.87, -0.55, 0.83, 0.37, 1.77, -0.96, -1.31 for the RL reference and 0.30, -1.15, -0.52, 0.78, 0.36, 1.77, -0.98, -1.13 for WCT reference, respectively. Relative errors between the reconstruction and the original signal were higher for WCT compared to RL reference (median error of 0.19 vs. 0.11). Reconstructed signals at offset-optimized positions for AtCM are visualized in Figure 3.

4. Discussion

The best position to measure APWD is the one with the smallest deviation to IAAT. Heuristically, the positions yielding signals characterized by an early on- and late offset, as well as by a clear delineation and high amplitude to facilitate measurements, should serve this purpose. Moreover, the optimized position should be easily accessible and generalizable across anatomical variations. Our results indicate that electrodes on the medial superior chest, placed superior to the conventional V1/V2 electrodes, could improve APWD measurements. Notably, limited anatomical variability in the sternum area and spatial proximity to existing ECG leads should reduce inter-individual variability and facilitate clinical usability. Overall, onset optimized positions were located slightly more to the right compared to offset optimized positions, aligning with the atrial activation starting in the right atrium. Given the close proximity of optimal regions and consistently high feature values in neighboring areas, a single electrode appears sufficient and is preferable in terms of usability. Considering that the P-wave offset is typically more challenging to detect, an offset-optimized lead should be more beneficial in clinical practice. While the RL reference yielded more promising results compared to WCT reference, the latter can be integrated more easily in clinical practice. Hence, the derived linear combinations of the standard 12-lead ECG signals to approximate the signals at the new positions could be a useful alternative, also enabling retrospective analysis. The derived optimized locations are not covered by the standard ECG lead system, however they align with optimized lead systems for the atria and the standard P-wave proposed in literature [19, 20], although those were mainly focusing on the overall P-wave amplitude. Moreover, the optimized region on the left posterior lateral chest for WCT reference aligns with previous results to increase left atrial P-wave signal energy [18]. However, as posteriorly placed electrodes pose practical challenges and tend to be more noisy,

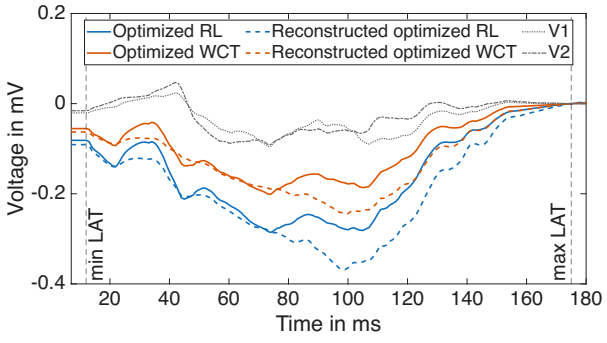


Figure 3: Signals and reconstruction from the 12-lead ECG at the center of the offset-optimized regions for atrial cardiomyopathy (AtCM) vs. V1 and V2 for a randomly chosen model with AtCM. Signals were aligned to the isoelectric line for the offset. RL: Right leg, WCT: Wilson's central terminal, LAT: Local activation time.

an anterior setup is preferred.

Overall, consistent results were observed across all torso models, suggesting a "one size fits all approach". While the used models did not allow for a sex-specific analysis, sex differences seem to be reflected by some eigenmodes of the torso SSM. Accordingly, sex differences should be assessed in future studies. Furthermore, future work could analyze P-wave morphology at the optimized positions, which is used to stage AtCM severity [21]. Finally, for successful clinical translation, APWD measurements at the derived positions must demonstrate superior agreement with the invasively measured IAAT [7] compared to APWD measurement from the conventional 12-lead ECG.

This study supports the hypothesis that optimized electrodes could improve APWD measurements by showing that unipolar electrodes placed above V1/V2 improve signal quality. The results further suggest that a single optimized electrode configuration may be widely applicable, which would facilitate clinical APWD analysis and allow the use of wearables for AtCM screening. Ideally, non-invasive APWD measurement at optimized positions enables more precise identification and staging of AtCM.

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