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Quantitative assessment of ventricular far field removal techniques for clinical unipolar electrograms

Abstract: The incidence of atrial tachycardia steadily increases in industrial nations. During invasive electrophysiological studies, a catheter measures electrograms within the atrium to assist detailed diagnosis and treatment planning. With unipolar and bipolar electrograms, two different acquisition modes are clinically available. Unipolar electrograms have several advantages over bipolar electrograms. However, unipolar electrograms are more affected by noise and the ventricular far field. Therefore, only bipolar electrograms are typically used in clinical settings.

A recently published ventricular far field removal technique models the ventricular far field by a set of dipoles and yielded promising results in a simulation study. However, the method lacks quantitative clinical validation.

Therefore, we adapted the technique to clinical needs and applied it to data sets of two patients using four different lengths of the removal window. Results were compared quantitatively by a tailored residual error measure.

The used method resulted in a median reduction of the ventricular far field by approximately 89% using a removal window of optimal length for both patients.

The results showed that the dipole method provides an alternative to other VFF removal techniques in clinical practice because it can reveal AA originally hidden by VFF without leading to a prolongation of the electrophysiological study.

Keywords: electroanatomic mapping, atrial electrograms, unipolar electrograms, ventricular far field removal.

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1 Introduction

Atrial tachycardia poses a steadily expanding problem in industrial countries. Atrial mapping is an important step in the diagnosis and treatment procedure. It is performed during a minimally invasive electrophysiological study with a catheter measuring electrograms within the atrium. Unipolar electrograms are the potential measured inside the atria in reference to a presumably indifferent reference potential. Bipolar electrograms are the result of the subtraction of two unipolar electrograms. Commonly used bipolar electrograms (bEGMs) have several disadvantages like the dependence on catheter orientation and lower spatial resolution.

Unipolar electrograms (uEGMs) do not have these detriments but are more affected by the ventricular far field (VFF) and noise. The VFF is caused by the depolarization and repolarization of the ventricles and can interfere with the clinically relevant atrial activity (AA) in time and frequency domain [1]. In the past, VFF removal techniques [1][2] have typically not been used in clinical practice because of major disadvantages such as the prolongation of the electrophysiological study.

Recently developed VFF removal techniques yielded promising results in a simulation study [3] and do not entail a prolongation of the clinical procedure. However, these techniques lack quantitative clinical validation. In this study we adapted the technique that yielded the best results in a simulation study [3] to clinical needs, applied it to data sets of two patients, and assessed the quality of VFF removal.

2 Methods

2.1 VFF removal technique

The VFF was estimated using the dipole method [3]. This technique builds a spatio-temporal model from a training data of previously recorded atrial electrograms. The recordings were aligned by the R-peak and should contain only VFF. This study focused on training data generated from electrograms

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during cardiac rhythms with temporally separated atrial and ventricular activity. If the removal window is chosen short enough, the training data did not contain AA per definition. We used separate spatial models for each time step k relative to the R-peak. The spatial course of the VFF was modeled as interference of electrical potentials emerging from a set of dipoles placed in the ventricles. The electric potential $\Phi_k(r)$ at a position r assuming discrete dipole positions r_i and a homogeneous volume conductor is given by:

$$\boldsymbol{\Phi_k(r)} = \boldsymbol{\Phi_{k,0}} + \sum_{\boldsymbol{i=1}}^{\boldsymbol{N_{Dip}}} \frac{\boldsymbol{1}}{\boldsymbol{4\pi\kappa}} \frac{\boldsymbol{(r-r_i)}}{\boldsymbol{|r-r_i|^3}} \boldsymbol{J_{k,i}} \tag{1}$$

with $\Phi_{k,0}$ being the reference potential, N_{Dip} being the number of dipoles, κ being the conductivity, $\mathrm{r_i}$ being the position of dipole i, and $J_{k,i}$ being the impressed current densities into the three spatial directions of dipole i.

The dipole method used $\Phi_{k,0}$ and $J_{k,i}$ as parameter of the model, which form the parameter vector c_k. c_k is an $n \times 1$ vector and the number of free state variables n is given by $n = 3 \cdot N_{Dip} + 1$.

In the training phase, c_k was fitted with least square optimizing to the matrix form of equation 1: $\Phi_k = X \cdot c_k$. Φ_k is an $m \times 1$ vector with the potential of each VFF segment in the training data. X is an $m \times n$ matrix mapping the parameter vector c_k to the potential vector Φ_k according to equation 1. Therefore, the first column of X contained ones and represented the coefficients of the reference potential. The following rows contained the coefficients of the impressed current densities of the dipoles in the three spatial directions according to the second summand of equation 1.

For subsequent VFF removal, the trained parameter vector c_k was known and X could be calculated using the dipole positions and the positions of the electrodes which recorded the uEGMs subject to VFF removal. Then, the VFF can be estimated easily using the same formula: $\Phi_k = X \cdot c_k$. Subsequently, the VFF was subtracted from the target uEGMs.

2.2 Removal window

We adjusted the lengths of the removal windows to make them patient-specific by determining the start and the end of the QRS-complex and the end of the T-wave for all heartbeats contained in the body surface electrocardiogram (ECG). We chose the length of the part of the adaptive removal window before the R-peak t_l and after the R-peak t_r using following formulas for each patient:

$$t_l = \overline{QR}$$
$$t_r = \overline{RS} + \overline{ST} \cdot x$$

with $\overline{QR}$ being the median duration between the start of the QRS-complex and the R-peak, $\overline{RS}$ being the median duration between the R-peak and the end of the QRS-complex, $\overline{ST}$ being the median duration between the end of the QRS-complex and the end of the T-wave, and $x \in [0,1]$ being the factor to modify the length.

The adaptive removal window with a variation factor of $x = 0.5$ was most similar to the removal window of a previous simulation study which used a removal window of 50 samples before and 200 samples after the R-peak with a sample rate of 953.674 Hz [3].

In this study we applied distinct removal windows by choosing $x \in \{0, 0.25, 0.5, 0.75, 1\}$.

2.3 Quality criterion

We assessed the quality of the VFF removal by creating a reference which was assumed to be the optimal target output. For uEGMs recorded during a cardiac rhythm with atrial and ventricular activity being separated in time, the reference should only represent the changes in the baseline and no other activity. Therefore, the reference consisted out of a spline that was fitted between the means of 10 samples with a sample rate of 953.674 Hz before and after each removal window.

We used the maximum deviation ϵ_{MD} between the reference and the output uEGM for each removal window as quality criterion since it represented the remaining VFF removal error. The median of the errors ϵ_{MD} of all segments of one patient is referred to as $\overline{\epsilon_{MD}}$.

2.4 Clinical data

We used the clinical data sets of two exemplary patients that were recorded at the Städtisches Klinikum Karlsruhe. The data sets contained the following information:

- uEGMs of a 64-pole IntellaMap Orion^{TM} catheter at 953.674 Hz
- Location of each electrode of the Orion^{TM} catheter at 20 Hz
- 12 lead ECG at 953.674 Hz
- uEGMs of an 8-pole coronary sinus (CS) catheter at 953.674 Hz
- Geometry of the left atrium (LA)

Each patient was recorded during sensed paced uEGM sequences, meaning that every other sinus beat was followed by a paced beat stimulated by a pacing catheter in the coronary sinus. We trained the VFF model with the sensed paced maps, and subsequently subtracted the model from the same map to remove the VFF.

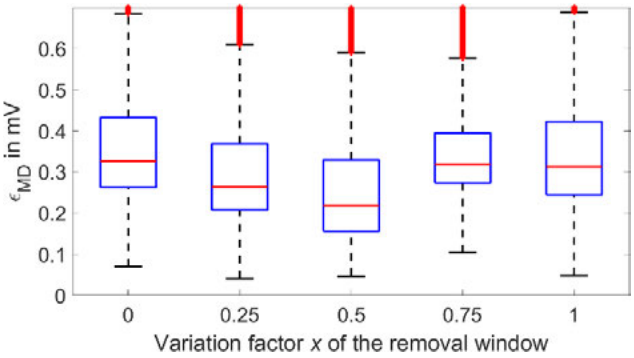

Figure 1: Maximum deviation error ϵ_{MD} for patient 1 of all segments using different lengths of the removal window

We used all R-peaks and electrodes as a starting point but removed segments from the assessment and training data because of filtering artifacts, pacing artifacts, atrial activity, strong baseline wander, strong deviation from the mean ECG morphology, measurements outside the atria, and unphysiologically high amplitudes. The segments to be removed were detected automatically. The VFF was modeled using 100 dipoles that were placed automatically in the ventricles. The ventricular geometry was approximated by a partially hollow box that was placed based on the geometry of the LA.

3 Results

The training data and assessment included approximately 50,000 to 90,000 VFF segments per patient. This corresponds to a deletion of ~15 to 50% due to artifacts or similar (Sec. 2.4) in relation to the raw data, depending on the length of the removal window.

VFF removal reduced the median VFF of patient 1 by 88.49% - 89.57% depending on the removal window used.

The median error $\overline{\epsilon_{MD}}$ of patient 1 had a minimum at 0.22 mV (equals a reduction by 89.57%) for the removal window using the variation factor 0.5 (Fig. 1).

The VFF of patient 2 was reduced by 82.05% - 88.95% depending on the removal window used. The median error $\overline{\epsilon_{MD}}$ of patient 2 had the highest value of 0.32 mV (equals a reduction of 82.05%) using the variation factor 0.5 (Fig. 2). Both smaller factors lead to a similar median of 0.19 mV (equals a reduction of ~89%).

Compared to other spatio-temporal models such as the polynomial model [3], the dipole method performed slightly better and was more robust in terms of the number of free state variables.

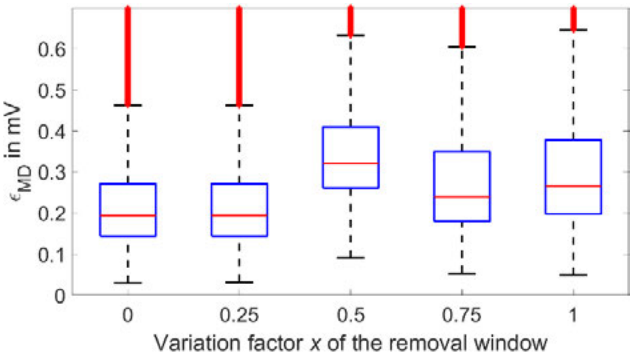

Figure 2: Maximum deviation error ϵ_{MD} for patient 2 of all segments using different lengths of the removal window

Patient 1 showed a mildly pronounced ventricular repolarization in the uEGM which was not included in the smaller removal windows (Fig. 3 a & b). The long removal windows tended to be removed from training and assessment more often because of pacing artifacts (Fig. 3 c II & 4 c II), and early AA because of a change of the cardiac rhythm (Fig. 3 c III).

Patient 2 showed a more pronounced ventricular repolarization in the uEGM with reference to patient 1 (Fig. 4). Parts of the repolarization are included using a variation factor greater than zero. If the end of the removal window is during the ventricular repolarization, the VFF free uEGM shows discontinuities (Fig. 4 b).

4 Discussion

We showed that applying the dipole method to uEGM can reduce the VFF significantly in clinical setups. The remaining VFF is smaller than the AA of interest but not entirely negligible. Therefore, VFF removal can reveal AA initially hidden by VFF and is an alternative to blanking during the QRS-complex. This makes the resulting uEGM easier to interpret during visual inspection by cardiologists and provides a better starting point for unipolar voltage maps and unipolar local activation time maps.

Blanked unipolar voltage mapping provides no benefit over bipolar voltage mapping [4]. However, clinical studies are needed to assess the added value of unipolar mapping after VFF removal compared to more robust bipolar mapping.

The length of the removal window should be selected on a patient-specific basis to avoid large discontinuities such as those seen for patient 2. For patients such as patient 1, consideration should be given whether the ventricular repolarization is a confounding factor in the VFF free signal and whether it can be omitted during VFF removal. Omitting

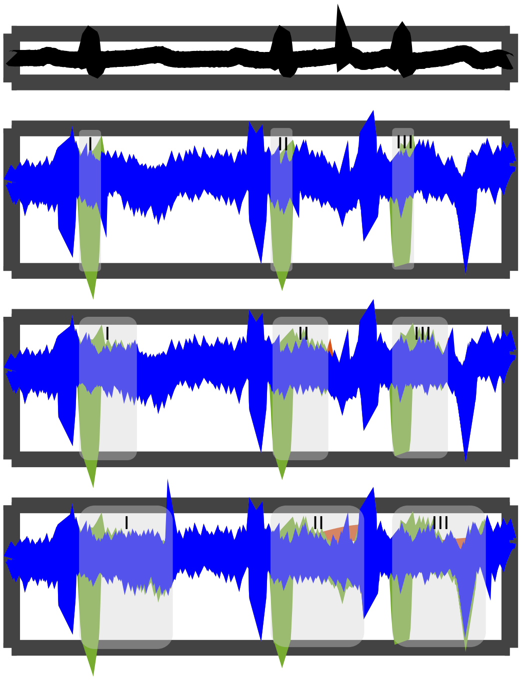

Figure 3: Exemplary segment of the signals of patient 1 using the variation factors 0 (a), 0.5 (b), and 1 (c). ECG lead in black, raw uEGM in green, reference in orange, and VFF free uEGM in blue. The removal windows (I, II, and III) are highlighted in gray.

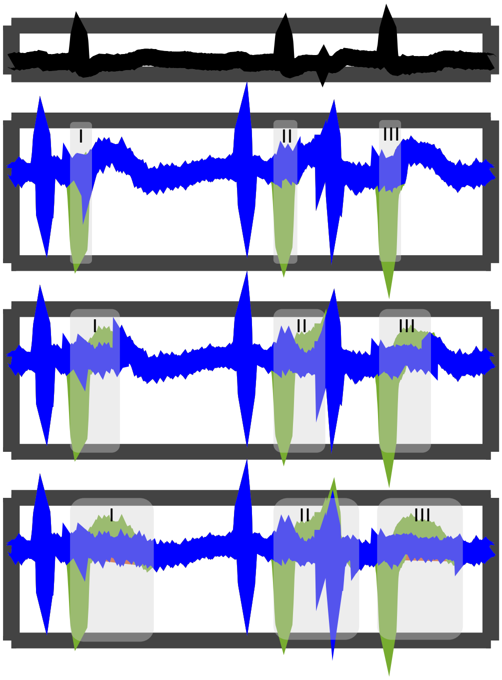

Figure 4: Exemplary segment of the signals of patient 2 using the variation factors 0 (a), 0.5 (b), and 1 (c). ECG lead in black, raw uEGM in green, reference in orange, and VFF free uEGM in blue. The removal windows (I, II, and III) are highlighted in gray.

the ventricular repolarization yields larger training data and prevents failures in the artifact detection.

Figure 3 and 4 indicate that it might be useful to differentiate between SR beats (I), SR beats before pacing (II) and paced beats (III) because they have different expressions of the ventricular depolarization and repolarization and the beats II and III tended to include artifacts and AA more frequently when using larger removal windows. One could use separate training data for each beat class and adapt the lengths of the removal windows accordingly. It must be investigated which training data performs best for which target rhythm, especially when moving forward to VFF removal during atrial tachycardia.

To eliminate discontinuities at the borders of the removal window in general, it seems reasonable to adapt the dipole method to a continuous VFF removal without removal windows. However, possible realizations and the resulting improvement in quality have yet to be analyzed.

In conclusion, we showed the capabilities of the dipole method, but also indications of possible improvements. The clinical benefit e.g., on the ablation success rate, remains to be investigated.

Author Statement

No funding involved. No conflict of interest. Informed consent has been obtained from all individuals included in this study. The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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