Inverse Solution Accuracy Using 12-Lead ECG vs 9 Significant Electrodes Derived by Greedy Algorithm

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Abstract

The inverse problem of electrocardiography is solved using potential recordings from numerous torso electrodes. However, there is a growing interest in minimizing the number of used electrodes to enhance clinical applicability.

A total of 8 datasets from patients with pacemakers obtained from the EDGAR database were used. The inverse problem assuming a single dipole cardiac source was solved for 3 different electrode configurations. The configurations included all 196 ± 28 electrodes, 9 corresponding to the 12-lead ECG, and the 9 most significant electrodes. The significance of the electrodes was derived by the greedy algorithm from the singular value decomposition of the transfer matrix. The accuracy of the inverse solution was expressed as the localization error (LE) computed as the Euclidean distance between the pacemaker electrode and the inverse solution.

The average LE for all 8 datasets using all torso electrodes was 26.1 ± 6.1 mm, whereas using 12-lead ECG electrodes yielded a LE of 40.5 ± 23.1 mm, and the greedy algorithm's selection resulted in a LE of 29.6 ± 14.0 mm. The results suggest that the use of the most significant electrodes outperformed the use of the 12-lead ECG. The study emphasizes the need for back electrodes for an accurate inverse solution.

1. Introduction

Electrocardiographic Imaging (ECGI), also known as the inverse problem of electrocardiography, aims to non-invasively reconstruct the heart's electrical activity. This reconstruction relies on capturing body surface potentials (BSPs) gathered from numerous electrodes placed on the surface of the torso. Usually, tens to hundreds of electrodes are used to obtain comprehensive spatial information about the heart's electrical field [1]. Regrettably, many electrodes make this approach impractical for routine clinical use. Thus, researchers study how to reduce the number of used electrodes while maintaining the accuracy of the solution [2] to improve the practicality of ECGI in clinical settings.

Several studies showed that the inverse problem can be solved accurately using a smaller number of electrodes; however, the number of electrodes needed is not yet identified [2], [3]. Currently, solution of the inverse problem just using electrodes of the 12-lead ECG gains interest since those measurements are easily executed and the datasets of recorded 12-lead ECG are easily available. The results show that the inverse problem can be accurately solved using the data recorded by the 12-lead ECG [4][5]. Nevertheless, the research indicates that, unlike the 12-lead ECG, which exclusively uses anterior electrodes, including posterior electrodes is essential for a more accurate solution of the inverse problem [4].

In this work, the accuracy of the inverse solution for a single dipole cardiac source using 9 electrodes of the 12-lead ECG and the 9 most significant electrodes is investigated and compared to the inverse solution using all electrodes.

2. Data and Methods

2.1. EP Solutions data

In this work, EP Solutions data obtained from the EDGAR database (https://www.ecg-imaging.org/edgar-database) [6] was used. In total, 5 patients with implanted pacemakers underwent body surface potential mapping (BSPM) with the Amycard 01C EP system using up to 220 (196 ± 28) torso electrodes. The BSPs were recorded during the pacing by the pacemakers' electrodes positioned in the right ventricle (RV) and left ventricle (LV). In summary, data from 5 patients with RV pacing and 3 patients with additional LV pacing were used.

For each patient, a 3D triangular geometric model of the ventricles (endo-epicardial) and the torso were constructed based on CT scans. Furthermore, the CT scans were used to determine the precise positions of the torso electrodes and the pacemakers' electrodes. More detailed information about the EP Solutions dataset can be found in [7].

2.2. Methods

In the context of EP Solutions data, the goal of the inverse solution is to localize the initiation point of the heart's electrical activity, which corresponds to the position of the pacemaker's tip. The inverse problem was solved using the equation

$$Sc = T^{+}\Phi_B \quad (1)$$

where S_c is the cardiac source, T^{+} is a pseudoinverse of the transfer matrix T and Φ_B are BSPs recorded on the torso. Here, the cardiac source S_c is described as a single dipole with a fixed position and variable orientation. The transfer matrix T represents the relationship between the cardiac sources and the recorded signals in each torso electrode. The transfer matrix was computed using the boundary element method (BEM) assuming a homogeneous volume conductor. The single dipole cardiac source can be positioned in each node of a 3D triangular mesh of the ventricles. The inverse problem was solved for the earliest phase of the depolarization cycle ($t \leq 30$ ms). The single dipole that best describes the cardiac activity within this short time cycle was chosen based on the criterion of minimal relative residual error (RRE). For each dipole, the RRE was computed as the Euclidean norm of the difference between the measured map Φ_B and the map computed by that dipole. More details about the inverse solution using a single dipole cardiac source can be found in [3].

Overall, the solution of the inverse problem was computed for 3 configurations shown in Figure 1:

1) using all torso electrodes,
2) using 9 electrodes corresponding to the positions of the 12 lead ECG electrodes,
3) using the 9 most significant electrodes selected by the greedy selection algorithm.

The 9 electrodes that align with the positions of the 12-lead ECG electrodes (configuration 2) and 9 most significant electrodes (configuration 3) were selected from the entire set of electrodes used in BSPM. In both configurations, unipolar leads measured against Wilson Central Terminal were used.

A brief overview of the selection process for 9 significant electrodes (configuration 3) is provided, with further details available in [3]. The significance of each torso electrode was derived using the singular value decomposition of the transfer matrix T corresponding to the approximate position of the cardiac source computed using all electrodes. Using SVD, the matrix T was decomposed into orthogonal matrices U and V and rectangular matrix Σ with singular values on its diagonal. The singular values provide insight into the significance of the electrode space and cardiac source space (columns of U and V, respectively). A higher singular value indicates greater significance. Consequently, we select combinations of electrodes that maximize the sum of these singular values. First, the initial combination of 4 electrodes from all possible combinations of 4 electrodes was selected. Following this, a greedy selection process is applied. In each iteration, one electrode was added to the previously chosen combination of electrodes, continuing until the 9 most significant electrodes were identified.

To validate the inverse solution, the localization error (LE) was computed as the Euclidean distance between the position of the pacemakers' electrode and the inverse solution. The LE was computed for each dataset and all 3 configurations.

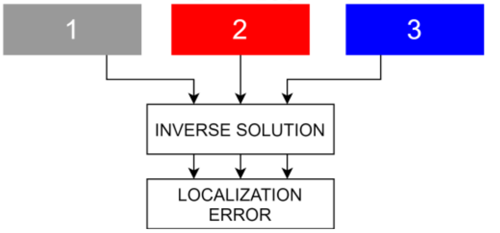

Figure 1. The pipeline of the study.

3. Results

First, the inverse problem was solved using all torso electrodes (configuration 1). The average LE computed for all patients was 26.1 ± 6.1 mm. The LE for the RV protocol was 28.1 ± 6.4 mm, while for the LV protocol, it was 22.6 ± 4.6 mm.

Second, the inverse problem was solved using 9 electrodes corresponding to the positions of the electrodes of the 12-lead ECG (configuration 2). The mean average LE was 40.5 ± 23.1 mm. The LEs for the RV and LV protocols were 32.9 ± 6.6 mm and 53.2 ± 6.4 mm, respectively.

Lastly, the inverse problem was solved using the 9 most significant electrodes (configuration 3) with an overall average LE of 29.6 ± 14.0 mm, 28.6 ± 5.5 mm for RV pacing, and 31.3 ± 24.8 mm for LV pacing. The LEs for each configuration, each patient, and protocol are shown in Table 1 and Figure 2.

Furthermore, Figure 3 shows the positions of the 9 significant electrodes chosen by the greedy algorithm in comparison to the standard 12-lead ECG configuration, for both RV and LV pacing and patient 024. For RV pacing, 4 electrodes were aligned with standard precordial leads of the 12-lead ECG, while the remaining significant electrodes were predominantly situated on the anterior side of the torso, nearer to the heart. Additionally, one electrode was identified in the posterior region. For LV pacing, the 4 most significant electrodes were located posteriorly, and the significant electrodes did not align with the electrodes of the 12-lead ECG.

Figure 4 displays the distribution of RRE values on the ventricular surface for the inverse solutions obtained using all electrodes (configuration 1) and 9 electrodes (configurations 2 and 3). Each node on the surface is assigned an RRE value. The smallest RRE values, representing the inversely computed origin of cardiac activity are depicted in the red color spectrum. It can be noticed that the region characterized by small RRE values is larger in solutions using 9 electrodes compared to that using all electrodes.

Table 1. The localization errors (LE) in mm for all 3 configurations.

	Configuration		
Patient	1	2	3
024 RV	38.6	36.7	31.9
026 RV	28.8	40.6	25.2
027 RV	23.8	31.2	20.4
033 RV	22.1	33.0	32.8
036 RV	27.2	23.0	32.5
024 LV	17.4	95.1	22.8
026 LV	24.6	41.5	59.3
033 LV	25.8	23.0	11.9

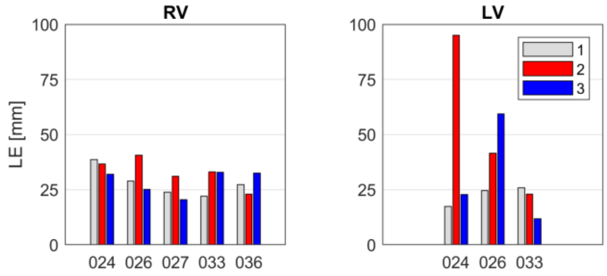

Figure 2. The localization errors (LE) in mm for all configurations and all patients.

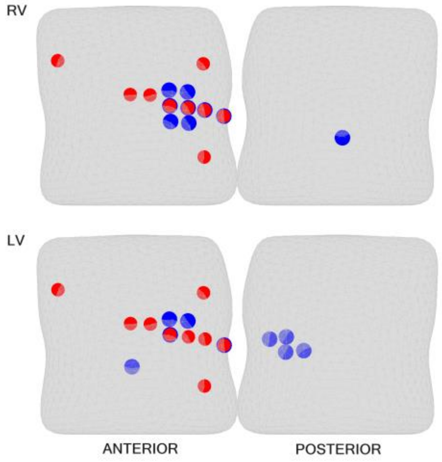

Figure 3. The positions of the 9 electrodes of the 12-lead ECG (red) and the 9 most significant electrodes (blue) depicted for patient 024.

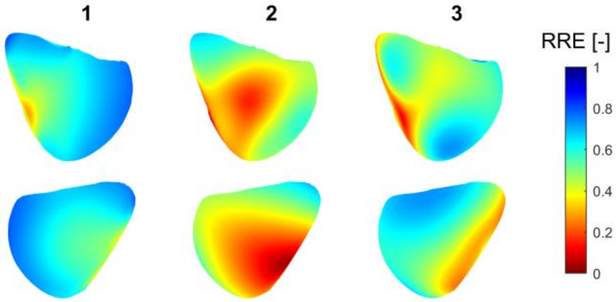

Figure 4. Distribution of RRE on ventricular mesh for patient 033 and LV pacing depicted for all configurations. The RRE is depicted for the anterior (upper panel) and posterior (lower panel) view.

4. Discussion

In this work, the accuracy of the inverse solution assuming a single dipole cardiac source using 9 electrodes of the 12-lead ECG and the 9 most significant electrodes was investigated. Our objective was to reconstruct the location of the pacemaker's electrode, whether it was positioned in the RV or the LV.

All results are summarized in Table 1 and Figure 2. Using all electrodes (configuration 1), we observed slightly superior results for the LV protocol, with an average LE of 22.6 ± 4.6 mm, as opposed to 28.1 ± 6.4 mm for the RV protocol. It's important to acknowledge that there was a discrepancy in the number of patients within each group, with 5 in the RV pacing group and 3 in the LV pacing group. Consequently, the average values were calculated based on different group sizes.

When using only 9 electrodes of the 12-lead ECG (configuration 2), the accuracy of localization deteriorated in both protocols. However, notably better results were observed for the RV protocol, with an average LE of 32.9 ± 6.6 mm, compared to the LV protocol, which had an average error of 53.2 ± 6.4 mm. These results can be explained by exploring the connection between the position of the cardiac source and the torso electrodes. In the RV pacing, the origin of the cardiac activity is in the apex of the RV, closer to the anterior region of the torso. Given that the electrodes of the 12-lead ECG are located anteriorly, they capture the initial milliseconds of the cardiac cycle more effectively in RV than in LV pacing. Nevertheless, improvement in LE was observed in two patients (024 and 036) for configuration 2 compared to configuration 1. Multiple factors can account for these outcomes. Among all the electrodes, there may be some with poor signal-to-noise ratios, and these can have a negative impact on the accuracy of the inverse solution.

When using the 9 most significant electrodes derived by the greedy algorithm (configuration 3), better results were observed for RV (28.6 ± 5.5 mm) than LV pacing (31.3 ± 24.8 mm). These results indicate that the inverse solution using the significant electrodes outperforms the approach using the 12-lead ECG electrodes.

It was shown that better accuracy was achieved when using all torso electrodes (configuration 1) compared to the use of the 9 most significant electrodes (configuration 3). Nevertheless, configuration 3 exhibited superior performance over configuration 1 in 4 out of the 8 computations. The higher average LE and standard deviation for configuration 3 were influenced by the high LE observed for patient 026 and LV pacing.

The positions of 9 electrodes for configurations 2 and 3 are shown for patient 024 in Figure 3. Overall, in RV pacing and configuration 3, the majority of the most significant electrodes were situated on the anterior side of the torso, specifically in the left half of the chest. Among the 4 out of 5 patients, one significant electrode was located on the posterior side, while in 1 patient, 2 electrodes were identified on the posterior side. In LV pacing, a greater number of significant electrodes were situated posteriorly. Specifically, in 2 out of 3 patients, 4 electrodes were identified posteriorly, and in 1 patient, 3 electrodes were found in the posterior position. Once more, a connection exists between the position of the cardiac source and the placement of torso electrodes. In LV pacing, the cardiac source is situated closer to the posterior side, necessitating the use of posterior electrodes to capture the initial milliseconds of the cardiac cycle. However, the results for both protocols indicate the importance of using electrodes on the patient's back as was indicated in [4].

Despite the study's findings suggesting that the inverse problem can be solved using only 9 electrodes, it is important to acknowledge that the results obtained using a small number of electrodes should be evaluated carefully. It can be seen in Figure 4 that identifying the node with the lowest RRE could pose a challenge when using a small number of electrodes.

Regrettably, our findings were derived from relatively small sample size and focused only on LV and RV pacing, potentially limiting their generalizability to different cases. Furthermore, the number and positions of the torso electrodes varied between patients. Thus, it could influence the positions of electrodes for configuration 3. Furthermore, the significance of the torso electrodes was derived using a patient-specific transfer matrix corresponding to inversely estimated origin of the cardiac activity using all electrodes. To identify the "optimal placement" of the 9 most significant electrodes, the significance at each node in the cardiac mesh across various patients should be accessed.

5. Conclusion

Our study investigated the accuracy of an inverse solution for localizing pacemaker electrodes placed in the RV and LV using different electrode configurations. The results suggest that using all torso electrodes led to a higher accuracy than using 9 electrodes of the 12-lead ECG or the 9 most significant electrodes. Furthermore, the results of the study suggest that the accurate solution of the inverse problem assuming a single dipole cardiac source cannot be obtained using electrodes of the 12-lead ECG. To obtain more precise results, electrodes on the patients’ back need to be used.

Acknowledgments

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