Unexpected Errors in the Electrocardiographic Forward Problem

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Abstract

Previous studies have compared recorded torso potentials with electrocardiographic forward solutions from a pericardial cage. In this study, we introduce new comparisons of the forward solutions from the sock and cage with each other and with respect to the measured potentials on the torso. The forward problem of electrocardiographic imaging is expected to achieve high levels of accuracy since it is mathematically well posed. However, unexpectedly high residual errors remain between the computed and measured torso signals in experiments. A possible source of these errors is the limited spatial coverage of the cardiac sources in most experiments; most capture potentials only from the ventricles. To resolve the relationship between spatial coverage and the accuracy of the forward simulations, we combined two methods of capturing cardiac potentials using a 240-electrode sock and a 256-electrode cage, both surrounding a heart suspended in a 192-electrode torso tank. We analyzed beats from three pacing sites and calculated the RMSE, spatial correlation, and temporal correlation. We found that the forward solutions using the sock as the cardiac source were poorer compared to those obtained from the cage. In this study, we explore the differences in forward solution accuracy using the sock and the cage and suggest some possible explanations for these differences.

1. Introduction

Electrocardiographic imaging (ECGI) is a noninvasive technique utilized as both a diagnostic and a research tool to reconstruct the bioelectrical activity of the heart. [1, 2] The forward problem describes the relationship between the electrical activity of the heart and the resulting electrical potentials on the torso. [3, 4] The forward problem is considered to be well solved as it is mathematically well posed and supported by numerical and computational techniques. [2] However, the residual errors seen in experimental validation studies and occurring between the computed and measured torso signals are still problematic. [2, 3] Previous studies have investigated a range of possible sources of lingering error in the forward problem, with recent research suggesting that incomplete cardiac source sampling is one of the major contributors to such errors. [2] Obtaining an accurate forward solution is necessary to achieve the best possible results in the ill-posed inverse problem. To systematically evaluate this problem, we have reported previous experiments that compared measurements of potentials recorded on the torso tank against a set of forward solutions that project cardiac potentials from electrograms measured on a high-resolution pericardial cage. [2, 5] The motivation for this approach came from earlier studies from our group suggesting that the lack of cardiac sampling over the atrial surface reduces the accuracy of the forward solution. [6] These studies found higher agreement between forward solutions and measurements compared to those previously reported [3] and they support the hypothesis that incomplete source sampling is a key aspect of lingering forward solution errors.

The cage used in these recent studies provides excellent coverage, however, it is a viable experimental tool only in a torso tank. More frequently, researchers and clinicians capture cardiac potentials directly from the epicardial and endocardial surfaces of the ventricles. The problem remains, then, to compensate for the resulting limited spatial sampling in electrocardiographic forward solutions.

To explore this problem, we compared the forward solutions generated from the pericardial cage array to solutions generated from an epicardial sock array in the same experiments. As expected, we found that the forward solutions based on the epicardial sock were substantially and consistently worse than solutions generated from the pericardial cage. Here, we enumerate possible causes of these errors and the means to address them in order to improve the performance of ECGI.

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2. Methods

Experimental Preparation: The experimental preparation consisted of a perfused, isolated heart suspended in a torso-shaped tank, as described previously. [2, 7] The isolated heart was instrumented with both a 240-electrode epicardial sock and a 256-electrode pericardial cage. The heart and recording arrays were then submerged in an electrolyte-filed torso tank with 192 electrodes embedded in the shell and electrical signals recorded simultaneously from all three electrode arrays.[8] Resulting signals were filtered, baseline corrected, and fiducialized using the open-source software PFEIFER. [9] To register the sock, cage, and torso geometries, we used the GRÖMeR system that we developed for this purpose. [2, 7] The experiments were approved by the Institutional Animal Care and Use Committee of the University of Utah, protocol number 17–04016 (approved on 05/17/2017).

Beat Morphologies: For this study, we focused on three activation sequences: sinus rhythm and pacing from the anterior left ventricle (aVP), and the posterior left ventricle (pVP). The pacing rate was held constant at 171 BPM and we captured 40 beats for each activation sequence.

Forward solution computation: We used the boundary element method with epicardial and cage potentials as the sources to estimate the torso-surface potentials in a homogeneous volume conductor. These projection methods were implemented in a combination of MATLAB and the Forward/Inverse Toolkit in the SCIRun problem-solving environment. [10]

Statistics/Evaluation Metrics: We compared forward solutions from both the sock and the cage to the measured torso surface electrograms according to three metrics: root-mean-square error (RMSE), spatial correlation (SC), and temporal correlation (TC). [4, 11] We evaluated these metrics separately for each heartbeat of each activation sequence and reported averages and ranges as box plots.

3. Results

Figure 1 shows the evaluation metrics for the computed forward solutions for both the cage and the sock. The sock returned consistently and substantially higher median RMSE values of 0.19 mV, 0.21 mV, and 0.13 mV for aVP, pVP, and sinus, respectively, compared to cage-derived errors of only 0.12 mV, 0.12 mV, and 0.05 mV for the same beats. The results for both correlations supported these trends: the median SC values following aVP were 0.98 for the cage and 0.89 for the sock, and following pVP were 0.97 for the cage and 0.89 for the sock. The differences in the SC following sinus rhythm were even more dramatic, with the sock returning a value of 0.59, whereas the cage correlation was about 1.5 times larger with a value of 0.92. The values for TC were similar but with an even larger spread overall, the largest for the sinus beats. The values for aVP were 0.99 for the cage and 0.60 for the sock, for pVP were 0.96 for the cage and 0.47 for the sock, and for the sinus were 0.99 for the cage and 0.30 for the sock. In general, the sock also returned more variability in the error metrics, as shown in the height of the boxes in Figure 1.

Figure 2 shows an example from the peak of the R-wave of an aVP beat. The figure shows measurements from both the sock and the cage as well as the computed and measured values from the torso tank electrodes. Visually, the potentials projected from the cage onto the torso had greater magnitude than the measured values, but showed a more accurate spatial pattern compared to the projections from the sock. The maximum and minimum torso potentials were 1.2 mV and -1.1 mV for the sock, 2.6 mV and -2.2 mV for the cage, and 1.7 mV and -1.5 mV for the measured values.

4. Discussion and Conclusions

In this study, we investigated the electrocardiographic forward problem and its ability to project measured cardiac potentials to the torso surface, which we also measured. The goal was to compare projections from an epicardial sock to those from a cage that surrounded the heart with complete spatial coverage and similar resolution. The two ventricularly paced beats returned similar values for all three statistics analyzed. The sinus beats demonstrated the same trends as the ventricularly paced beats, but with different values and ranges. Overall, our results showed that the forward solutions from the cage were considerably more accurate, *i.e.,* lower RMSE values and higher SC and TC compared to the forward solutions from the sock. These differences in accuracy were largest for the sinus beats. These are the first reported studies to include source potentials from both the epicardial sock and pericardial cage simultaneously and thus allowed direct comparisons not previously available. The representation of the volume conductor and geometric model required to solve the forward problem is a key factor to consider. The epicardial sock covers only the ventricles and thus misses potentials over the top of the heart; we have shown previously that this lack of coverage can contribute to inaccuracies in the recordings. [2, 6] To address the lack of coverage of the epicardial sock, we have explored Laplacian interpolation as an effective technique to reconstruct the missing surface potentials. [6] A further source of geometric error is the flexible shape of the sock, which the forward solution assumes to be static and rigid. The sock shape is only approximately captured in experiments and can lead to errors during registration. On the other hand, the cage has

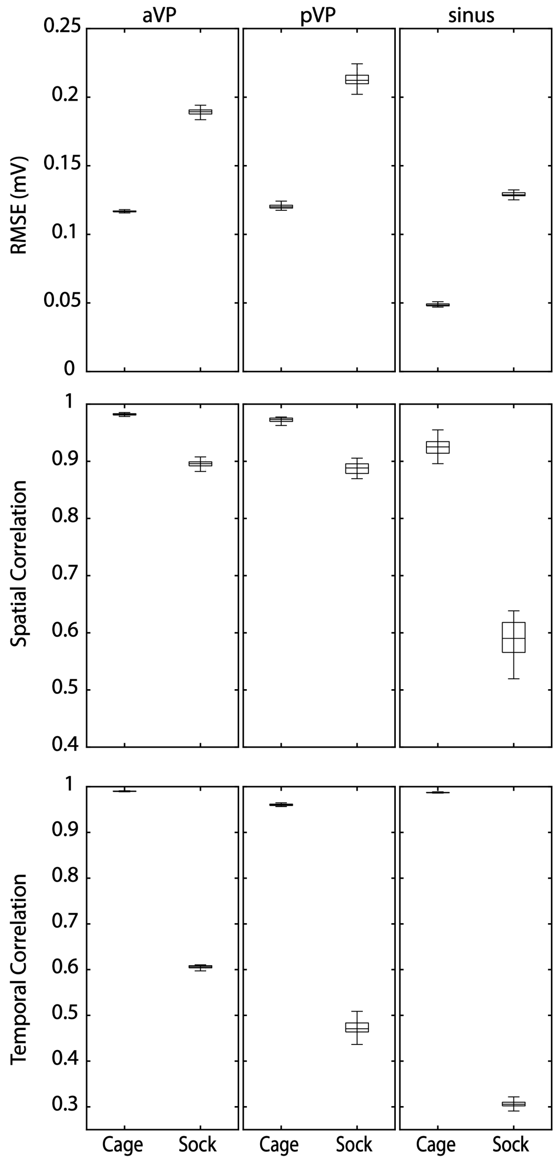

Figure 1. Forward problem accuracy statistics. RMSE (mV), spatial correlation (SC), and temporal correlation (TC) both for the sock and cage potentials projected to the torso. Statistics were performed over all 40 beats per each morphology analyzed: anterior ventricular paced (aVP), posterior ventricular paced (pVP), and sinus.

a rigid structure that provides the advantages of both uniform coverage over the whole heart and a stable structure that can be captured in the geometric model with high precision (within a few millimeters).

A second factor to consider is the relative distance of electrodes from the heart and the resulting spatial resolution of the epicardial sampling. Although both the cage and the sock had approximately the same number of electrodes, the average distance between neighboring electrodes on the cage was 21 mm whereas it was closer on the sock at approximately 10 mm. The cage sits offset from the heart, on average 1.9 cm from the epicardial surface. Previous studies showed that sampling location is as important as sampling density. [6]

A further consequence is distance to the torso tank, the distance bridged by the projection; for the cage, average spacing to the nearest torso electrode was only 6.4 cm compared to 8.3 cm for the sock. This combination of a smoother source representation and shorter distance would be expected to result in better fidelity of projections from the cage than the sock, as our results suggest.

These findings suggest many future studies, analyses, and experiments to obtain accurate forward solutions using only ventricular sampling. Obtaining an accurate forward solution (which is well posed) using this dataset is relevant to achieve good results in the inverse solution (which is ill posed). To start addressing this problem, we will use the complete potential measurements from the cage to improve the forward solution accuracy from the sock. Specifically, we will try to achieve solution accuracy similar to the cage by reconstructing the atrial activity on the sock using various reconstruction methods including interpolation and machine learning.

These studies will help us improve the forward solutions from the epicardial sock in our validated data. This validated dataset will then be used to develop more robust inverse formulations.

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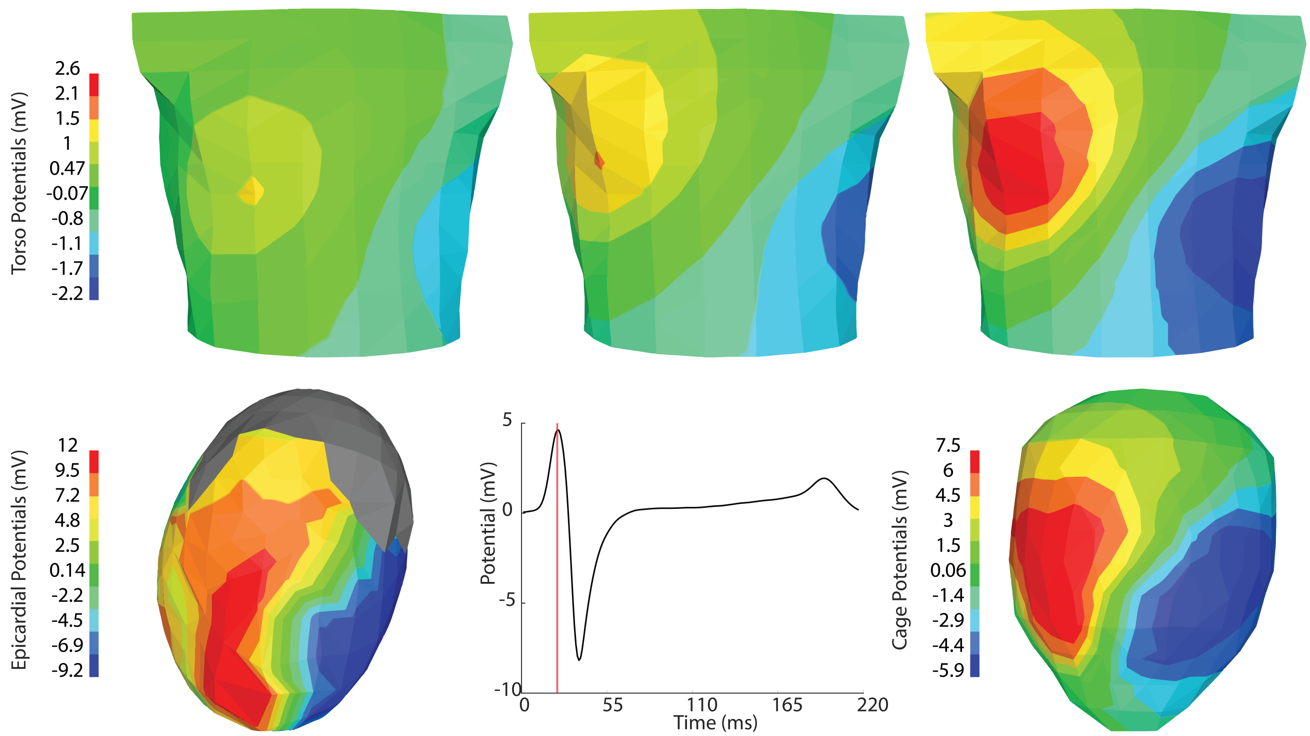

Figure 2. Reconstruction of surface potentials at the time of the peak of the R-wave of a representative beat paced from the anterior left ventricle. The top row contains the torso potentials projected from the sock (top left), experimentally recorded (top center), and projected from the cage (top right). The bottom row contains experimentally recorded sock potentials (bottom left), the corresponding electrogram with a vertical red line marking the time instant (bottom center), and experimentally recorded cage potentials (bottom right). The top color bar corresponds to the torso maps, the bottom left color bar to the epicardial map, and the bottom right color bar to the cage map.

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