In-vivo Evaluation of Reduced-Lead-Systems in Noninvasive Reconstruction and Localization of Cardiac Electrical Activity

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Abstract

Noninvasive imaging of electrical activity of the heart has increasingly gained attention last decades. Heart-surface potentials are reconstructed from a torso-heart geometry and body-surface potentials recorded from tens to hundreds of body-surface electrodes. However, it remains an open question how many electrodes are needed to accurately reconstruct heart-surface potentials. In a canine model, we reconstructed epicardial electrograms and activation locations, investigating the use of a full-lead system, consisting of 169 well connected body-surface electrodes, and reduced-lead systems: using half or a third of the electrodes, or a minimalistic set of the default 12-lead ECG.

Correlation coefficients indicate that the quality of the reconstructed electrograms remains stable to a third of the electrodes, and decreases with fewer electrodes. Similarly, the mismatch between the detected origin of a beat and known pacing location decreases when fewer body-surface electrodes are used. However, when only 9 or 10 electrodes are available for pacing localization, the median mismatch is 30mm, only marginally higher than when half of the electrodes are used, although with a significant error spread up to 65mm.

These results indicate that for specific purposes (such as detecting the origin of an extrasystolic beat), a lower number of body-surface electrodes can provide noninvasive electrocardiographic imaging results that might still be useful for a clinical purpose.

1. Introduction

Electrocardiographic imaging (ECGI) aims at noninvasively reconstructing the electrical activity of the heart, based on body-surface potential measurements and a patient-specific torso-heart geometry, see Figure 1. [8, 7] This is achieved by solving the inverse problem of electrocardiography. In the last decades, much progress has been made in ECGI and clinical applications occur with increasing frequency. [5] However, many open questions remain. One clinically relevant question is what the optimal number of electrodes is that is necessary to obtain reconstructions of high quality.

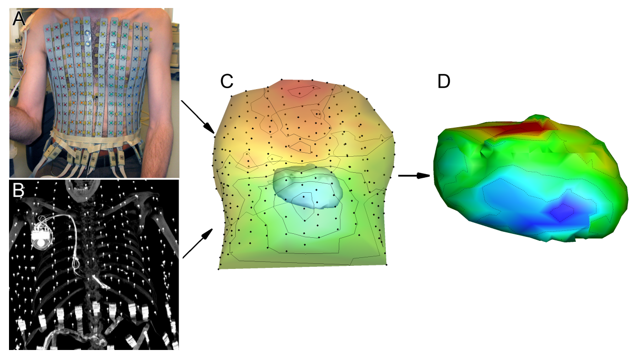

Figure 1. Noninvasive electrocardiographic imaging as it is applied in humans. From measured body-surface potentials (A) and a CT scan (B) a torso-heart geometry is created (C) and epicardial potentials are reconstructed (D).

To be able to reconstruct electrical activity of the heart, measurements of the projected potentials on the body surface should be taken at sufficient positions at anterior, posterior and lateral sides of the patients torso. These represent the natural output of the electromagnetic (forward) propagation of cardiac electrical signals to the body surface. However, the minimum number of body-surface electrodes and their optimal positioning remains a subject of discussion, but is usually taken to be far more than the nine electrodes of the 12-lead ECG. Currently used setups include 64 [6], 120 [9] or 256 [10] electrodes. Recently, the use of only the standard 12-lead ECG was shown to be worthwhile in some cases, but using this small number of body-surface electrodes has not been validated thoroughly [2].

In this study, we investigate the use of lead-systems with fewer leads, starting from 169 well-connected electrodes, ultimately with only 3 body-surface electrodes. The result-

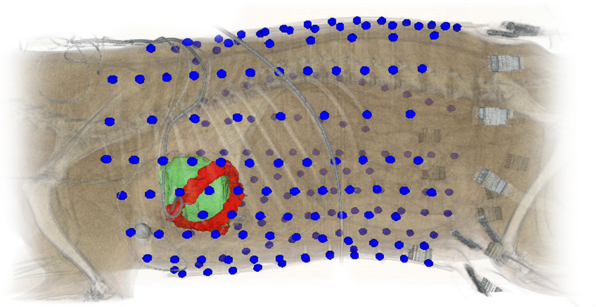

Figure 2. Validation data as collected in a canine experiment. Body-surface potentials were recorded with 192 electrodes and epicardial potentials with 99 implanted elctrodes. A CT scan was performed to localize the electrodes and epicardial surface.

ing epicardial electrograms and origins of activation are validated in a canine experiment with simultaneous recordings of body-surface potentials, epicardial potentials, and known pacing locations.

2. Experimental evaluation

To investigate the used of reduced-lead sets in noninvasive electrocardiographic imaging, validation data was acquired in a dog experiment, see Figure 2. In a healthy dog, electrodes were implanted around the epicardium via a thoracotomy and body-surface electrodes were attached to the torso. A homogeneous geometry was digitized from a CT scan and consisted of the body-surface electrodes and the epicardial surface. Potential recordings were obtained simultaneously on the body-surface and on the epicardium. The transfer matrix, relating the electrical activity at the heart-surface to the body-surface, was computed with methods available from the SCIrun software repository. [1] For this transfer matrix, all 192 body-surface electrodes were used.

Due to the ill-posed nature of the inverse problem, it is very sensitive to noise. Additional information is needed to arrive at a realistic solution, which is called regularization. [5] We have applied the much used zeroth order Tikhonov regularization, which requires the reconstructed potentials to be suitably small, penalizing big amplitudes (which are unrealistic, but often present in solutions influenced by ill-posedness). The regularization parameter was determined using the L-curve corner. [4]

A local electrogram was reconstructed for each node of the digitized epicardial surface. Of all implanted epicardial electrodes, 52-73 electrodes recorded a good signal (number of well-connected electrodes could change per beat). Those ground-truth electrograms were compared to the reconstructed electrograms from the corresponding (closest) virtual epicardial node.

Selected epicardial electrodes were also used for pacing. In that case, the activation time (defined by the earliest maximum $-dV/dt$) on each virtual epicardial node was determined. However, due to noise and fractionation, pinpointing the correct maximum can be difficult. To overcome this, we applied a spatio-temporal approach that takes the electrograms of the neighbouring virtual nodes into account. [3] In these paced beats, the reconstructed activation times were used to determine the location of first activation and compared to the known pacing location.

2.1. Reduced-lead setups

Of the 192 body-surface electrodes, 169 electrodes had a connection to the skin that provided electrograms of high quality. This full set of well-connected electrodes was used to compare the reduced-lead sets to, see Figure 3. Reduced-lead sets were created by selecting only part of the electrode strips (visible as columns in the geometry). For example, the set 'Half 1' was based on selecting every other strip of electrodes; the set 'Half 2' was formed by its complement. Due to an uneven number of strips, one strip was included in both sets, resulting in a combined number of electrodes that exceeds the inital set. In a similar way, three sets of leads with 1/3 of the electrode strips were created. For comparison, also clinically more used sets were evaluated. The default 12-lead electrocardiogram is based on 9 electrodes, forming the '9-lead' set. In one set, an additional electrode on the right leg was included, resulting in the '10-lead' set. Ultimately, a 3-lead set was formed by Einthoven's triangle.

2.2. Statistical analysis

In one dog, 39 beats were analyzed. Pearson's correlation coefficients were computed for each recorded epicardial electrogram and the reconstructed epicardial electrogram on the closest virtual epicardial node. For 27 paced beats, the mismatch between the reconstructed location of earliest activation and known pacing location was determined. When paired statistical analysis was performed, we used Wilcoxon signed rank tests.

3. Results

Figure 4 shows the correlation coefficients for all 52-73 epicardial electrodes for all 39 beats, averaged per lead-setup. Clearly, a lower number of electrodes decreasing the reconstruction quality of the reconstructed electrograms, starting with a average correlation coefficient of 0.60, decreasing to approximately 0.55 when only a third of the electrodes is used, to 0.45 when only 9 or 10 electrodes are used, and to 0.35 when only three electrodes are used.

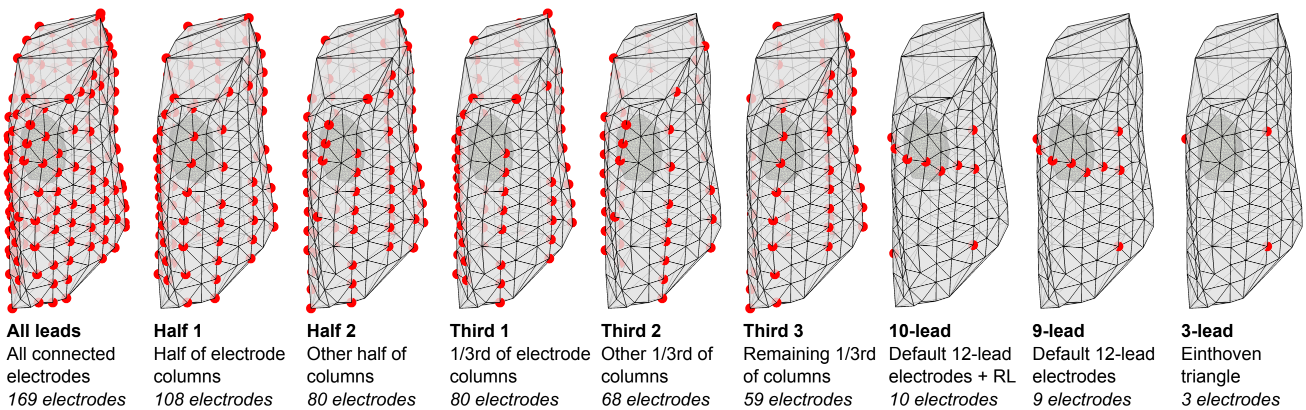

Figure 3. The full and reduced-lead setups used for noninvasive reconstruction of epicardial potentials and activation locations. The transparent mesh represents the body surface, and the heart surface is shown as well. The red dots in the full-lead setup represent all body-surface electrodes with a good recording quality. In the subsequent setups, only subsets of these electrodes are used.

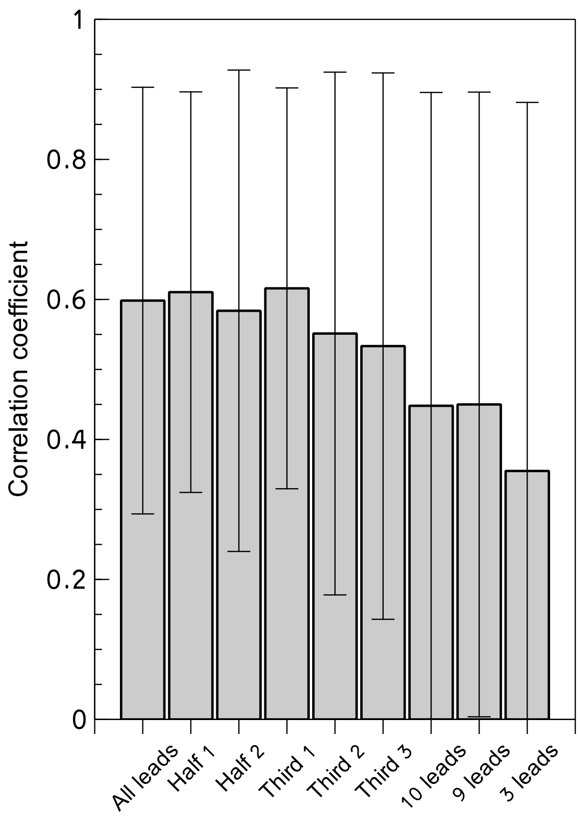

Figure 4. Correlation coefficients between reconstructed and recorded electrograms, averaged over all epicardial electrodes in all 39 beats in each lead setup.

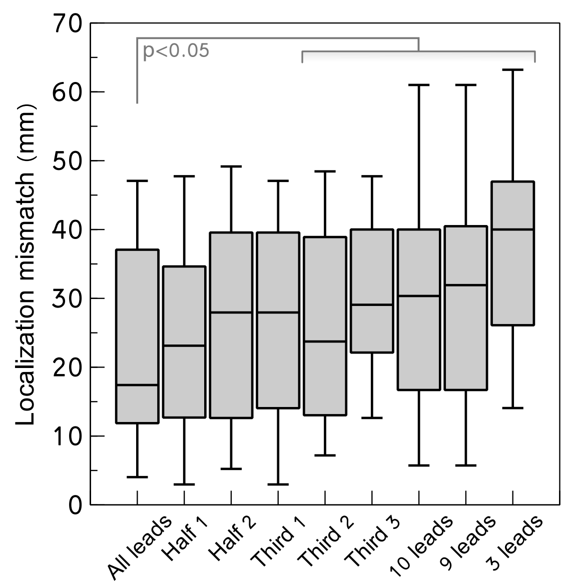

Figure 5. Boxplots of the mismatch between reconstructed and known locations of earlieast activation, for all 27 paced beats in each lead setup. Horizontal line in the box indicates the median; the box spans the range bewteen the first and third quartiles.

In Figure 5, the pacing mismatch for the 27 paced beats is shown as a boxplot per lead-setup. When all leads are used, there is a median mismatch of 18mm between the pacing location and reconstructed origin of the beat. When using half of the electrodes, this increases to 23mm and 28mm. In case of 9 or 10 electrodes, the median error is approximately 30mm. For a 3-lead setup, the median mismatch is 40mm.

4. Discussion

We have evaluated the effect of the number of body-surface electrodes on the quality of reconstruction of epicardial electrograms and pacing localization in a canine experiment. Correlation coefficients indicate that the quality of the reconstructed electrograms remain stable from 169 (set 'All leads') to 59 (set 'Third 3') electrodes. When only the 12-lead ECG electrodes are used, reconstruction quality decreases. Similarly, the mismatch between the detected origin of a beat and known pacing location decreases when fewer body-surface electrodes are used. However, it is striking that when only 9 or 10 electrodes are available for pacing localization, the median mismatch is only marginally higher than when half of the electrodes are used. This might be the result of the spatio-temporal approach when determining the activation times, in which neighbouring nodes on the virtual epicardial surface are taken into account when determining the activation times. This procedure also involves smoothing, which might be beneficial when only a few electrodes are used to reconstruct electrograms on thousands of epicardial nodes.

In this study, we have not investigated the effect of including a more detailed body-surface geometry in the transfer matrix. In all lead-setups, the transfer matrix was computed on the original 192 body-surface electrodes. A more detailed body-surface geometry might improve the reconstruction quality in reduced-lead setups even further.

Additionally, the regularization parameter was determined on the full set of electrodes. Selecting the regularization parameter per reduced-lead setup might be beneficial (selecting a more appropriate balance between the available information from the limited number of electrodes, and the need for regularization), but could also be disadvantageous (as simply less information is available to determine that balance).

In conclusion, these results indicate that for specific purposes (such as origin of an extrasystolic beat), a lower number of body-surface electrodes can provide results that are still useful for a clinical purpose. However, especially when using only a 12-lead setup as suggested by Van Dam [2], it is important to realize that although the median results are reasonable, there is a significant spread of the error, up to a 65mm mismatch.

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