Impact of electrode misplacement on the accuracy of 12-lead ECG synthesized from differential leads.

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Abstract – The sensitivity to electrode misplacement of the 12-lead ECG, synthesized from differential leads, was analyzed by simulating the electrode misplacement, with a help from interpolated body surface potential maps. The electrodes forming optimal differential leads were independently moved only on the lines defined by gradient vectors, calculated on the integral body surface potential map, obtained from juxtaposed average beats for each of the 47 multichannel ECGs used in the study. The 12-lead ECGs were synthesizes from the simulated moved differential leads and compared to the ECGs synthesized from the nominal electrodes' positions, by using correlation coefficients and RMSD. The results show that synthesized 12-lead ECGs are less accurate if electrodes with bigger associated gradients are misplaced, but also suggest that small displacements of up to 1 cm do not have a big influence on the synthesis quality. From the perspective of ECG synthesis, the presented methodology can be used to define an additional criterion for optimal triplets of differential leads selection, which will ensure that the differential lead triplet are optimal not only in terms of the quality of the synthesized leads, but also in terms of being minimally sensitive to electrode misplacement.

I. INTRODUCTION

A number of previous studies have shown that electrode misplacement of standard electrode positions, for the acquisition of the 12-lead ECG, can cause differences in ECG signals and their interpretation [1]. It has also been shown that misplacement of electrodes employed by a reduced-lead set {I, II, V2, V5}, has effects on synthesized 12-lead ECGs, in terms of increased root-mean-square deviation (RMSD), as the electrode distances from their nominal positions increase [2].

Body surface potential maps (BSPM) [3] have been used before for the purpose of simulating the electrode misplacement in standard 12-lead electrode set [4] or in a reduced-lead set [2]. They enable the measurements obtained from simulated misplaced electrodes to be synchronous in time with signals from other electrodes, but also enable position changes over distances smaller than the once possible to realize physically.

In this study, BSPM are used to investigate how the electrode misplacement effects 12-lead ECGs synthesized from differential leads (DLs). Differential leads [5] are bipolar leads that measure the potential between two closely placed body-surface electrodes. The DL measurements can be obtained by so called wireless body electrodes (WBEs) – novel devices that enable minimal obtrusion and wireless transmission of recorded signals [6]. Since there are an infinite number of possible directions of electrode misplacement, normally authors choose to restrict the simulation of electrode misplacement to only vertical and/or horizontal directions. In this study however, we consider the most significant direction for the electrode misplacement to be in the direction of the BSPM gradients on each electrode.

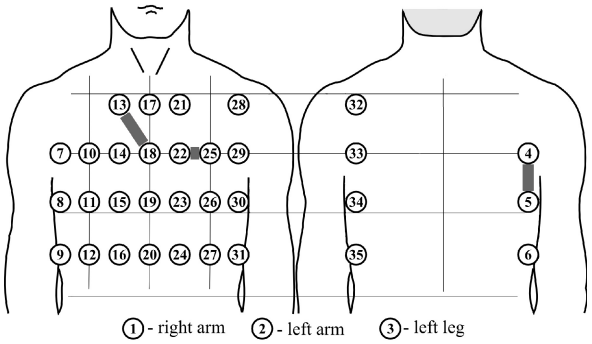

Figure 1. Schematic locations of multichannel ECG (MECG) electrodes on the chest (left) and the back (right). The gray lines represent the calculated optimal universal leads for the 12-lead ECG synthesis: {(13, 18), (22, 25), (4, 5)}.

In our previous studies, we have shown that it is possible to synthesize quality 12-lead ECG from three DLs [5]. By using our algorithm for selection of optimal DLs, we have also identified optimal universal positions of three DLs (see Fig. 1) from which 12-lead ECG can be synthesized by employing universal or personalized transformations [7]. In this study, we investigate the impact DLs' electrodes misplacement has on the 12-lead universal and personalized transformation. There is also the third approach to the synthesis in which both DLs positions and transformations are personalized. We have not investigated this fully-personalized approach for the electrode misplacement effect since for that approach a multichannel ECG (MECG) needs to be obtained from each person, which makes it possible to mark on the skin the positions of electrodes of the optimal personalized

DLs and thereby minimize the possibility of misplacement.

II. Methods

A. Studied data

Twenty healthy volunteers (13 male, 7 female, mean age ± SD = 50.6±9) with no previous medical record related to heart disease and with a normal 12-lead ECG, and twenty-seven patients (22 male, 5 female, mean age ± SD = 58±10), scheduled for a coronary artery bypass surgery, were included in our study. Informed consent was obtained from all the subjects before the study. A single MECG measurement was obtained from each person. For the data recording device and procedure please refer to [8]. The measurements were obtained during our previous studies [9]. The positions of the MECG electrodes are specified in Fig. 1.

The length of each measurement was 360 seconds. They were processed using MatLab (MathWorks, Inc.) where the average beats were obtained for each lead of the baseline corrected MECGs, by the procedure described in [7]. Note that the high-frequency noise is satisfactorily damped by the averaging.

B. Generic differential leads

A method of juxtaposing measurements was used: the average beats from each MECG were concatenated for each lead thus forming generic MECG leads. The generic DLs are formed by taking differences of juxtaposed MECG leads.

C. Body surface potential maps

For the interpolation of potentials between MECG electrodes, the cubic spline interpolation has been used to provide smooth transition of approximated data between measurement positions. The interpolated potential maps [10] were used for the simulation of electrode misplacements in each time instant. Additionally, an integral BSPM [11] was calculated for the generic differential leads. We will refer to this map as generic integral BSPM (GIBSPM). Since the GIBSPM is calculated from juxtaposed average beats from each person, it can be thought of as estimation of average integral map (for the whole beat) across all the persons covered by the study. The estimation is of course more precise as the variance of average beats lengths across different persons is smaller.

D. Experimental procedure

Gradient vectors were calculated from GIBSPM for each MECG electrode position. We have considered the worst-case scenario of electrode misplacement to be if the electrodes are moved on the line defined by associated gradients, since the gradients define the directions of fastest changes in potential. We have defined the movement of each electrode {13, 18, 4, 5, 22, 25} that makes the three optimal differential leads (see Fig. 1) in both directions of the gradient defined lines, up to 3 cm, in 0.5 cm steps. The electrodes were moved one at the time, i.e. while one electrode was moved the positions of all other electrodes were kept nominal.

For each person, five second intervals were identified in the MECGs and associated 12-lead ECG, that were not used for the calculation of universal positions and transformations used for the synthesis. For each person and for each independent movement of the six electrodes, the 12-lead ECG was calculated using the universal transformation, and by using personalized transformation. Here the simulated moved electrode measurement is taken from integral map for each time instant. The correlation coefficients (CCs) and RMSDs were calculated between the obtained synthesized 12-lead ECGs and 12-lead ECGs synthesized from the nominal electrode positions.

III. Results

Fig. 2 shows the calculated GIBSPM. The gradient vectors are oriented in the direction of increasing potential

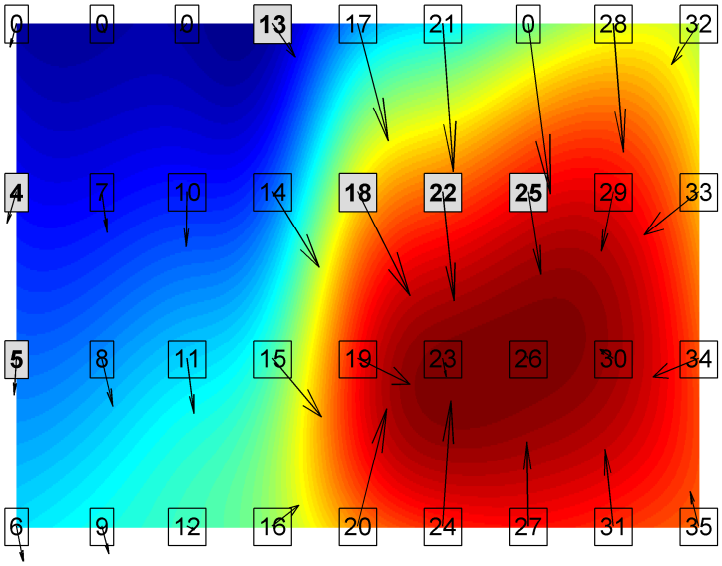

Figure 2. Generic integral BSPM (GIBSPM) for the juxtaposed whole average beats. Electrodes are organized in a matrix as defined by Fig.1. Positions without electrode are denoted with 0. Electrodes forming the optimal lead tripelt, the moved electrodes, are denoted with gray boxes.

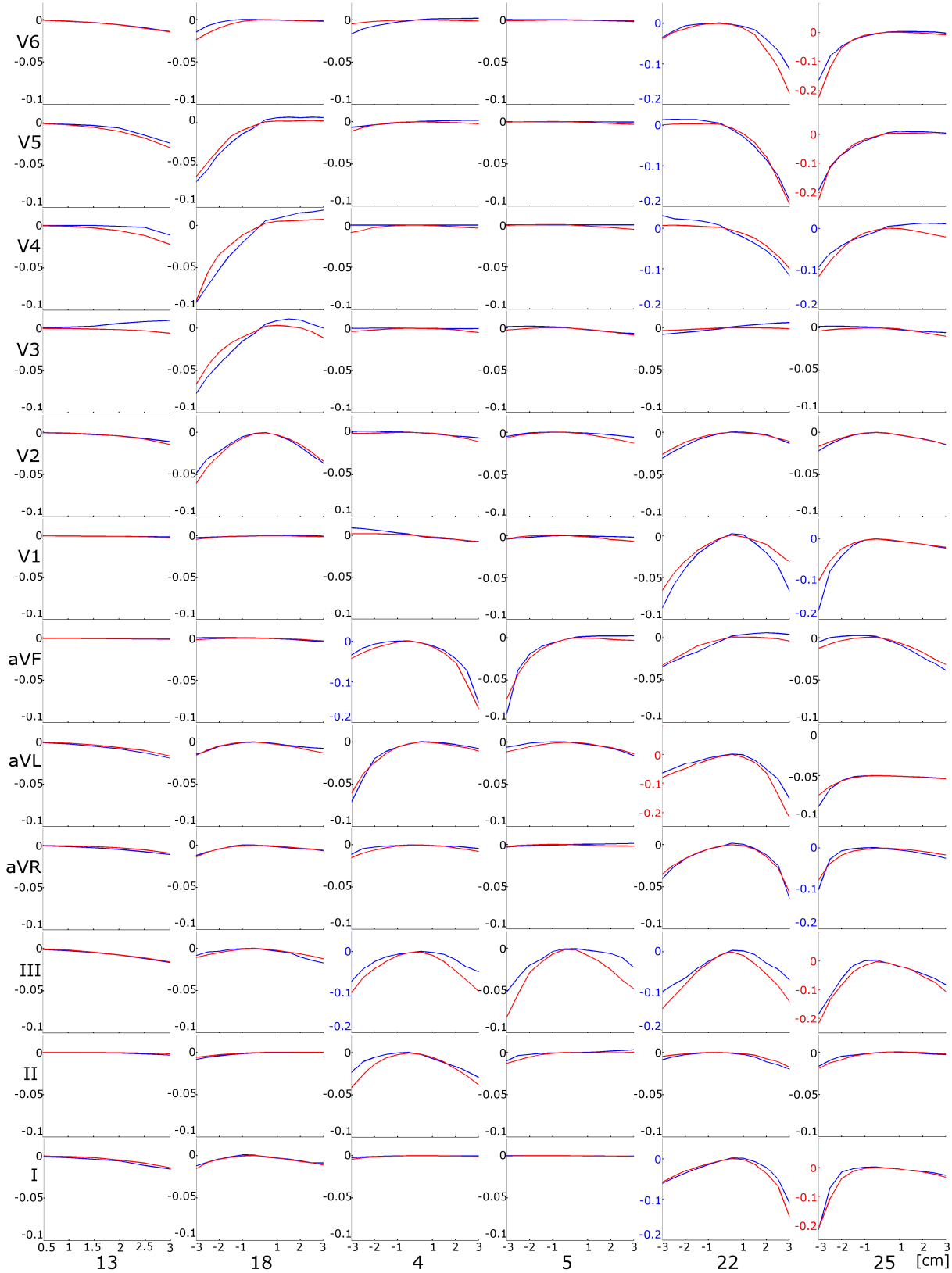

Figure 3. Median differences (dCCs) between CCs for misplaced position and the CCs obtained for nominal electrode positions (lower values imply lover synthesis quality). The CCs are calculated between target and synthesized leads. The columns represent the six electrodes. Each electrode was moved from -3 to 3 cm in steps of 0.5 cm (x axes), except for the electrode 13 which was moved from 0.5 to3 with the same step (0.5). Three scales used in the graphs: black for the dCCs above -0.1, blue for dCCs above -0.2, and red for dCCs below -0.2. Blue curves correspond to dCCs for universal transformation whereas the red line is for the personalized transformation.

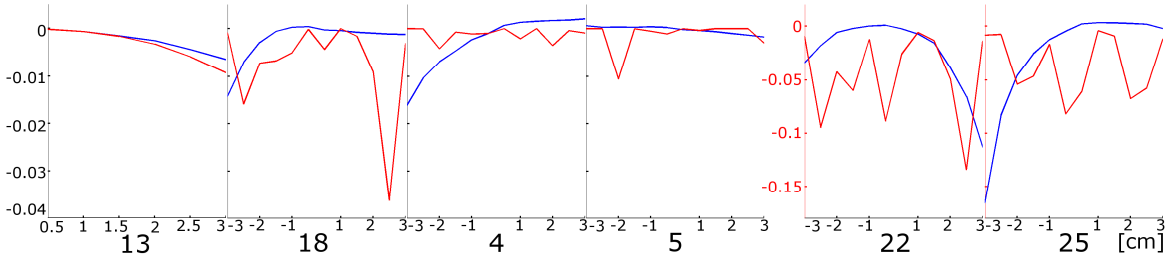

Figure 4. Median differences (dCCs) between CCs for misplaced position and the CCs obtained for nominal electrode positions across all leads of the 12-lead ECG (lower values imply lower synthesis quality). The CCs are calculated between target and synthesized leads. The columns represent the six electrodes. Each electrode was moved from -3 to 3 cm in steps of 0.5 cm (x axes), except the electrode 13 which was moved from 0.5 to 3 with the same step (0.5). Three scales used in the graphs: black for the dCCs above -0.04, red for dCCs below -0.15. Blue line corresponds to universal transformation whereas the red line is for the personalized transformation.

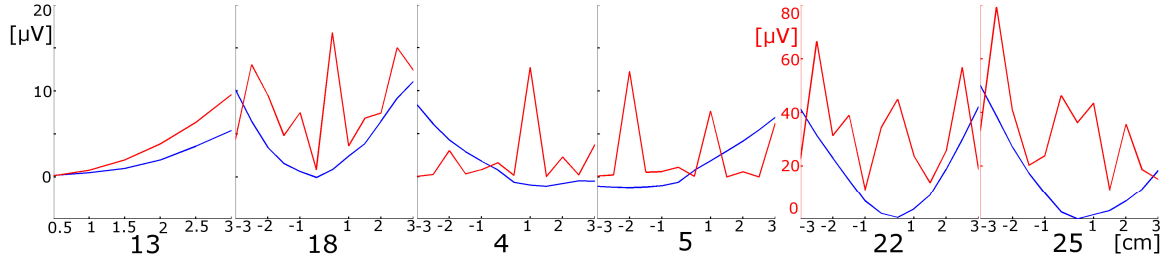

Figure 5. Median differences between RMSDs for misplaced position and the RMSDs obtained for nominal electrode positions across all leads of the 12-lead ECG (higher values imply lower synthesis quality). The RMSDs are calculated between target and synthesized leads. The columns represent the six electrodes. Each electrode was moved from -3 to 3 cm in steps of 0.5 cm (x axes) , except the electrode 13 which was moved from 0.5 to 3 with the same step (0.5). Two scales used in the graphs: black for the RMSDs below 20μV, red for RMSDs abow 60μV. Blue line corresponds to universal transformation whereas the red line is for the personalized transformation.

(positive direction). Gradient vectors for electrodes 4 and 5 point only slightly outside of the interpolated map. Therefore for these two electrodes, instead of using extrapolation, the gradients were just postulated to be pointing straight downward to keep them inside the map. For electrode 13 (also a boundary electrode) the misplacements were calculated only in the direction of its gradient (positive direction), and not in the negative direction since it falls out of the map.

Medians of calculated CCs between synthesized and target 12-lead ECGs are presented on Fig. 3 for each of the six electrodes and for each misplacement distance. The CCs were subtracted by the CCs obtained for the corresponding nominal electrodes positions and therefore negative values represent decrease in synthesis quality as each electrode is moved.

We have also calculated the median CC differences across all synthesized leads (Fig. 4). The analogous RMSD differences are presented on Fig.5.

IV. Discussion

It can be suspected by analyzing Fig. 3 that in most cases the synthesis using personalized transformation loses more in quality when electrodes are misplaced. This becomes obvious form Fig. 4 and Fig 5. Fig 4. shows that CCs distances from the CCs obtained for nominal positions are in general larger when personalized syntheses parameters are used (red lines). Similarly, Fig. 5 shows that RMSDs deviations from the RMSDs obtained for nominal electrode positions, are in general larger for the personalized transformation parameters (red lines).

These results are a bit unexpected since one would expect a more personalized synthesis algorithm to perform better in any aspect, compared to the universal one. Even though this shows that the approach with personalized transformation is more susceptible to electrode misplacement, it does not say that the approach with personalized transformation is inferior by any means. The results certainly show that the personalized approach loses more on the synthesized leads quality, but then again it has more to lose since it provides better synthesized 12-lead ECGs, from the nominal electrode positions [7].

All three figures show that as the misplacement increases, the synthesis quality decreases. Still, Fig. 3 points out that in general small misplacements in range [-1, 1] cm do not influence the synthesis significantly. It is also possible that a small misplacement even increases the synthesis quality (for example, lead V3 for electrode 18). There is however quite a big variation between the electrodes and between the synthesized leads. For example, lead V2 is much less vulnerable for any of the six electrode misplacements compared to lead III (Fig. 3).

Even more obvious is that electrodes 22 and 25 have the biggest influence on the synthesis quality (Fig, 3, 4, and 5). This can be explained by the fact that they together form one DL and are located in the GIBSPM area with fast potential changes – they both have big gradients (Fig. 2). Electrode 18 also has a much bigger gradient than electrodes 4, 5, and 13, and hence a higher impact on the synthesis quality (Fig. 4 and Fig. 5).

We have considered only displacements in the direction of gradient vectors obtained from GIBSPM. This

makes a good sense since the gradient is the direction of fastest potential change. Still the gradients were obtained for the whole beats but are in general different for different ECG segments or intervals. To apply the same approach, but concentrating only on a part of the beat, one would need to construct integral map only for the segment/interval of interest and calculate their gradients.

V. Conlusion

The results suggest that synthesized 12-lead ECGs are more distorted if electrodes with bigger associated gradients are misplaced. Additionally the results confirm what could be expected: as the electrodes are moved more from the nominal positions, the quality of the synthesized leads decreases in terms of CC and RMSD. Small displacements however, show only small decrease in CC and RMSD.

In this study, only one electrode is moved at a time. A possible extension of this work is to simulate simultaneous movements. Furthermore, this study employs only the CC and RMSD for comparing waveforms, but they can be rather crude in expressing similarities or finding differences between detailed waveform patterns. A small RMSD or a large CC can lead to differences in the diagnostic content of the synthesized and the target 12-lead ECG. Further work is therefore needed to assess the diagnostic accuracy of the ECGs synthesized from displaced electrodes.

Finally, the approach presented here can be employed as an additional criteria for selection of optimal DLs, for 12-lead ECG synthesis. As there are a number of combinations of three DLs that can be used for the synthesis of 12-lead ECG [7] (in this work only one combination was used), by applying sensitivity to misplacement as the additional criteria, another triplet can be obtained that is not only suitable in terms of the quality of the synthesized leads, but also in terms of being minimally sensitive to electrode misplacement.

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