Estimation and Reproducibility Issues in ECG Signal Monitoring. A Simulation Study

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Abstract. *Two Important issues of ECG telemonitoring are addressed by statistical modeling. The first one is related to the reproducibility due to inaccurate electrode replacements, the second one is due to inadequate signal estimations if only a limited number of leads are recorded instead of the complete 12-lead system and the unmeasured leads are estimated. The required data of the simulation were extracted from a database of body surface potential maps with 192 leads. The error terms were represented by correlation coefficients, RMS error histograms and Box and Whisker diagrams. The monitoring by I, II, and V2 leads is presented in depth.*

Keywords: ECG telemonitoring, electrode misplacement, signal information loss

1. Introduction

In ECG telemonitoring the diagnostic utility of the measurements is highly influenced by the appropriate cooperation of the patient. One of the key issues is related to the correct placement of the electrodes [1]. Obviously, the false placement could cause significant distortion in the recorded waveforms, eventually completely masking diagnostically meaningful changes. To ensure adequate reproducibility, the use of a limited set (e.g. limb leads) of electrodes instead of the 12-lead system gained a general acceptance [2]. However, the ease of electrode positioning is partly compensated by the loss of diagnostic information due to the lack of signal information carried by the unapplied (precordial) leads [3]. This paper addresses the problem in its complexity. Based on a representative body surface potential map database, both the expected effect of the electrode misplacements and the signal information loss due to the reduced lead-set is taken into consideration.

2. Material and methods

Body surface potential maps, BSPM, data of 150 subjects were used for the simulation. 50 normal subjects and 100 pathologic cases (15 inferior myocardial infarction, 15 posterior myocardial infarction, 15 anterior myocardial infarction, 20 ischemic heart disease, 10 Wolff-Parkinson-White syndrome, and 25 with previous malignant arrhythmia episodes) were used. All the measurements were taken by the 32-electrode limited lead system of Lux [4]. In the data processing phase from the 32 measured signals 160 additional thoracic potentials were estimated.
Subsequently, the standard 12 ECG leads were extracted from the 192 lead BSPMs. In the next step, the malpositioned electrode data were derived from the BSPM data by linear interpolation. In fact, the effect of a systematic misplacement of 1cm was estimated in four directions (up, down, left, right). The pattern differences of the correct and the misplaced leads were compared by correlation coefficients and by the rooted mean square, RMS, value of the difference signals. For a concise representation, the average parameters and the relevant standard deviations, SD, were stored lead-by-lead. For more deep analysis histograms, box and whisker diagrams were plotted.

In our study, we have focused on the expected performance of the I, II, V2 monitoring leads. Assuming, that at the beginning of a monitoring procedure the complete 12-lead ECG records are always available, an optimal estimation matrix T was computed for the use of optimal estimation of the leads not measured during the monitoring period itself. According to Lux et al., if P_1 is the vector of measured potentials and P_2 is the vector of the potential samples to be estimated, in the sense of the least square approach, the best estimate is given as:

$$P_2 = TP_1$$

where:

$$T = K_{12}^{'} K_{11}^{-1}$$

K_{11} is the covariance matrix of vector P_1 and K_{21} is the covariance matrix of vector P_2. According to the assumption mentioned above, from the data available when entering into the monitoring procedure, the T matrices can be calculated for all the patients individually or based on a large representative population for general. In our approach both possibility was tested (T_{general} and $T_{\text{personalized}}$) and the relevant performances were compared.
In the final step, the common effect of electrode misplacement and the error due to the estimated leads was compiled. Beyond the global faithfulness of the signals considered, the expected accuracy of parameters important from the point of monitoring (e.g. ST60) was tested as well.

3. Results

In this section, representative examples of the resultant electrode misplacement and estimation errors are shown for the precordial leads. In fact, V2 lead is a measured one; consequently, in the column of V2 the correlation and RMS errors are exclusively due to the misplacement. The lumped quality parameters (for V1, V3-V6) show, that using personalized transformation matrices the errors are significantly better than by the use of the general matrix. The RMS error can be twice as much with general T-matrix than with the personalized one (see V1, V3, V5).

Table 1. Combined effect of electrode displacement and lead estimation on the representation errors

	V1	V2	V3	V4	V5	V6
Average correlation (personalized T-matrix)	0,953	0,976	0,977	0,970	0,987	0,987
Average correlation (general T-matrix)	0,896	0,976	0,910	0,915	0,962	0,960
RMS value [μV] (personalized T-matrix)	57,878	67,390	70,715	43,167	27,111	24,862
RMS value (general T-matrix)	103,116	67,390	142,331	120,889	72,280	57,692
SD of correlation (personalized T-matrix)	0,089	0,042	0,04	0,061	0,036	0,038
SD of correlation (general T-matrix)	0,2	0,042	0,137	0,151	0,068	0,076
SD of RMS value [μV] (personalized T-matrix)	26,069	28,545	45,387	29,16	17,943	17,299
SD of RMS value [μV] (general T-matrix)	54,405	28,545	86,784	70,6	47,058	37,564

Table 1. summarizes the resultant effect of electrode misplacement (average of 1 cm displacements in each direction), and the errors due to the estimations of leads V1 and V3-V6. Examples in Fig.1. provide a deeper insight in the error distributions behind the lumped values shown in Table 1. The correlation coefficient and the RMS error distributions are shown for the personalized and for the general T matrices, as well. The superiority of the personalized estimations is obvious. However, in both cases the distributions are rather skewed, a few percentages of cases give rather modest values.

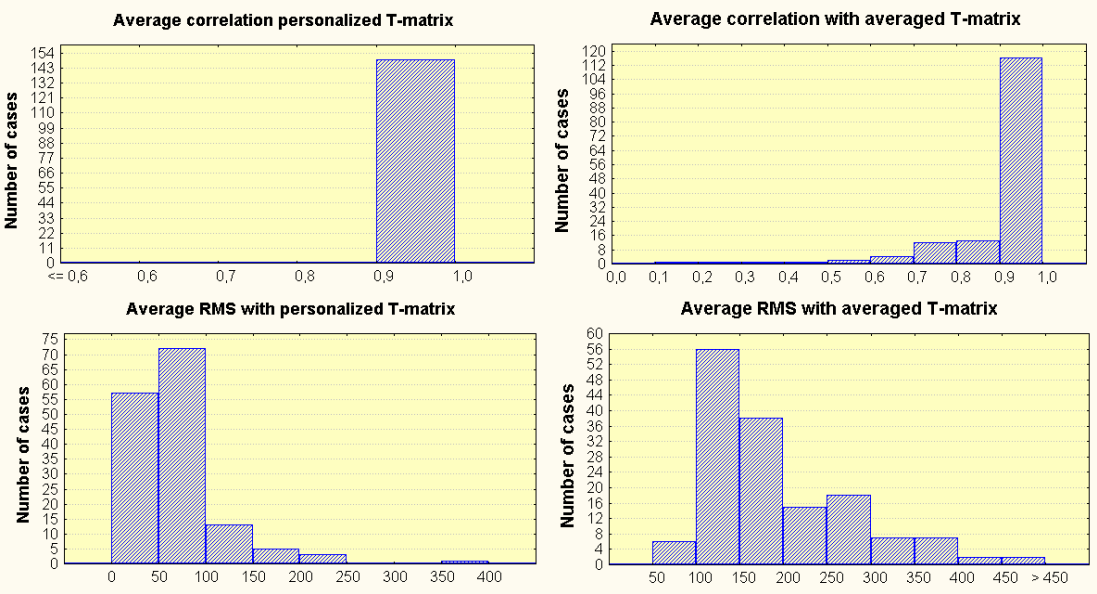

Fig. 1. Example for distribution of correlation (above), and RMS values[µV] (below) of the 150 subjects in lead V3. On the left side the results are with the personalized T matrices and on the right with general T-matrix.

In Fig.2. and Table 2. instead of the total ECG cycles, just the quality of a single parameter is presented. Specifically, the reproducibility of the ST60 parameter is shown, which is relevant from the point of view monitoring. In Fig.2, the Box and Whisker diagram demonstrates that though the median value and the interquartile distances are rather low, but the distribution is again skewed, with high RMS errors in few cases. According to this test, the estimates of V3 leads are especially sensitive.

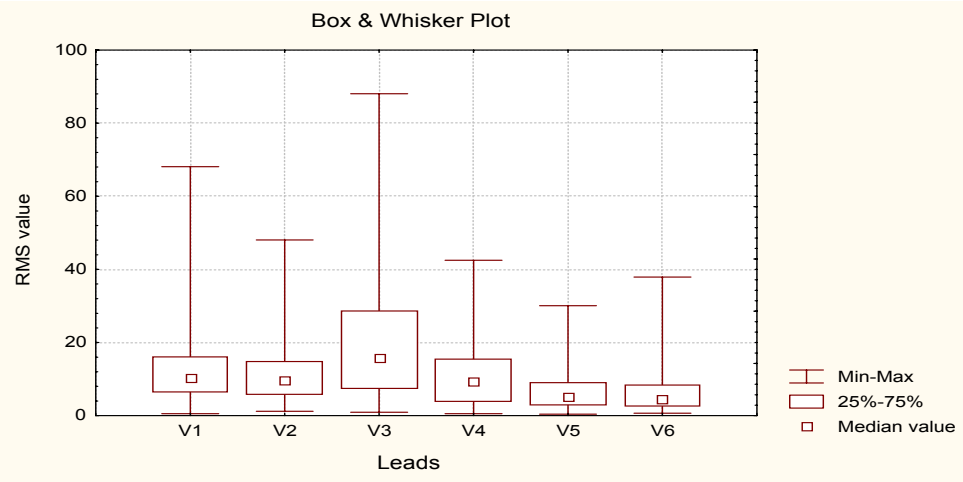

Fig. 2. Box & whisker plot of ST-60 error RMS values [µV], with personalized T matrix.

Table 2. Average RMS values of ST-60 errors with personalized T matrix.

	V1	V2	V3	V4	V5	V6
ST 60 [μV]	9,1	7,6	13,9	8,3	4,7	4,3

4. Conclusions

According to the study presented, for a long time ECG monitoring (e.g. under home-care conditions), the use of I, II, and V2 leads is a reasonable approach. As in all in these type monitoring scenarios, the measurement of the standardized 12-lead ECG is possible; we can obtain all the data necessary for an optimized estimation of the unmeasured precordial leads.
According to our results, the signal estimation quality is high enough to preserve the diagnostic information contained by the 12-lead system. In long term monitoring, the patient has to place the electrodes properly in the positions explained by his/her doctor. Obviously there is a risk of displacement errors. However, if the electrode displacement error can be kept small enough (in this study an error of 1 cm was assumed) even the combined error of the two effects studied should remain within an interval acceptable. The use of personalized estimation matrix shows a clear advantage over the general estimation matrix.

Acknowledgments

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