Framework for Testing of ECG Signal Quality Metrics

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Introduction. Market of wearable biomedical systems for continuous monitoring of biosignals like ECG, EEG, respiration and motion increased a lot during last few years [1]. Development of low energy precision electronics combined with smart textile technological innovations led to numerous researches towards convenient clinically relevant wearable applications based on smart textile, especially for electrocardiography. The main issue for the acceptance of textile electrodes is the signal quality. The performance of textile electrodes for ECG acquisition is usually validated only in terms of visual ECG signal shape evaluation [2]. Another approach for quality estimation is based on the quantitative metrics. Rattfalt L. *et all* [3] for validating the quality of conductive textile electrodes based ECG used detected heart beats comparing them to reference channel. Andreoni G. *et all* [4] used two leads (with reference electrodes and textile electrodes) to collect signal from simulator and subjects doing daily activities. Collected signal was compared with simultaneously recorded signal from reference medical grade Ag/AgCl electrodes and resulted in almost perfect performance using simulator and reduced performance depending on subject's activity. Four parameters were used for comparison of signals. These parameters included number of errors in QRS detection compared with reference, peak to peak amplitude of QRS compared with amplitude from signal simulator, QRS detection delay in 50 samples window and cross correlation between corresponding beats. Since conductive gel and pressure belt was used during these tests, the resulting performance was a lot better compared to what is expected from textile electrodes implemented in casual clothing. This type of clothing was used in another approach [5] during which an algorithm for rejection of ECG below quality threshold was developed. Since this kind of algorithm is dealing with harsh and unstable ECG signal while rejecting low quality samples and improving performance of whole record there is no standard methodology to test its performance.

The aim of this research was to develop framework to test the performance of the algorithm which is able to measure ECG signal quality and indicate corrupt data acquired with two leads textile electrodes.

Materials and methods. Hardware used in application was wireless BioNomadix two channel electrocardiograph (BIOPAC Systems, Inc, Goleta, CA) recording at 1000 Hz sampling frequency. One channel was dedicated for reference Ag/AgCl electrodes and textile electrodes were on second channel (see

Fig.1). Data used in this research was obtained using casual underwear shirts (5% spandex, 95% cotton) without skin preparation or conductive gel. Conductive textile sewed on the shirts (76% nylon, 24% spandex) was silver coated medical purpose fabric having less than 0.5 Ω/cm^2 electric resistance. Five records of average length of 200 seconds were recorded while subject was doing various activities including walking, running and jumping to provoke signal contamination.

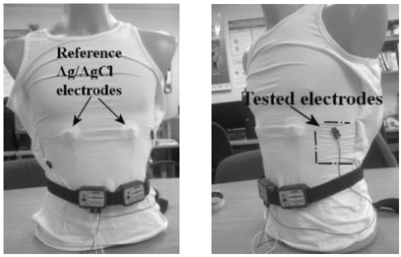

Fig. 1. Data acquisition setup used in algorithm performance test

Proposed framework for testing of ECG signal quality metrics is presented in Fig. 2. Reference signal is ECG signal acquired using clinical grade disposable electrodes. We assume that this signal has good quality for heart beat detection even during movement. For R wave detection the modified Pan-Tompkins algorithm is used [6]. These detected R waves and QRS complexes (ECG signal in time frame ±0.35 s regarding R wave) are used for the reference. ECG signal acquired using textile electrodes passes through the tested ECG quality estimation algorithm. In this research for illustration purposes only one simple algorithm was used [5]. Examined algorithm is based

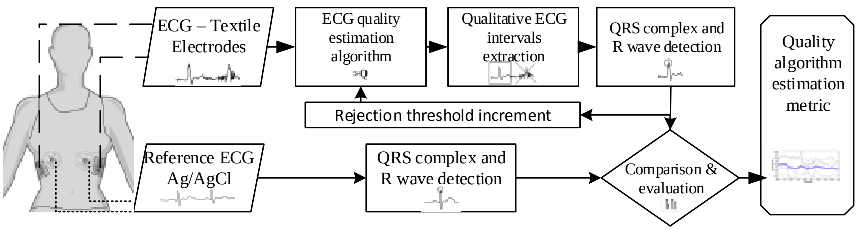

Fig. 2. Proposed framework for ECG quality algorithm performance testing

on continuous monitoring of signal amplitude filtered through differentiating and averaging filters. Corrupt ECG signal indication is based on the applied threshold value. Threshold value is specific for this algorithm and corresponds to differentiating and averaging filters result. This result is usually a number below 0.1 and can vary in terms of electrodes shape, material, size or location. In this case all records were recorded using same conditions and threshold values in range of 0.005 (whole record usually treated as good quality) and 0.05 (almost whole record usually treated as poor quality) was chosen. In order to evaluate proposed framework for ECG quality algorithm performance testing, dependency of tested algorithm performance on the chosen threshold range was found. Any other ECG quality algorithm might depend on more parameters which must be assessed during framework testing. Qualitative ECG intervals as indicated by the tested algorithm are extracted and passed to R wave and QRS complex detection. Then the comparison between this and reference channel data is performed. Since tested algorithm is threshold dependent an increased threshold value is fed back to tested algorithm on next iteration.

On the next step the comparison and evaluation of reference and tested R waves and QRS complexes are performed by calculating parameters described in Table 1.

Table 1. Parameters used for ECG quality evaluation

Parameter	Description
R wave detection error	Closest distance between detected R wave using reference and textile electrodes
Specificity and sensitivity	Specificity and sensitivity were calculated comparing detected R waves to reference R waves using standard equations. True positive was identified as a number of correctly (±2 samples comparing to reference) detected R waves. False positive was identified as a number non-correctly (more than ±2 samples away comparing to reference) detected R waves. True negative was identified as a number of all samples in a record minus number of R waves in tested record. False negative was identified as a number R waves in reference record minus number of correctly detected R waves.
"Qualitative" QRS complexes cross correlation	Average value of cross correlation of "qualitative" (as decided by the quality detection algorithm) QRS complexes with reference QRS complexes.
"Qualitative" R wave amplitude ratio	Average ratio between peak R wave amplitude value in "qualitative" segments and reference record.

Results. Results of the evaluated ECG signal quality detection algorithm are presented in figures 3-8.

Mean absolute R wave detection error (Fig. 3) shows that for low thresholds this error is big and tends to go before reaching minimum at threshold value of 0.02. Mean standard deviation (Fig. 4) of R wave detection error for all records reaches the minimum at 0.021 threshold value, and increases towards minimum and maximum threshold values.

R wave amplitude ratios (see Fig. 5) did not reveal any tendency which could be derived by any optimum threshold value. Usage of the ECG signal quality algorithm allows getting very high specificity (see Fig. 6) which is very important factor in highly noise contaminated signal. The specificity curve reveals optimal threshold value that is also equal to 0.021. Sensitivity (Fig. 7) widely varies on records and is at the lowest point within low threshold, but also reaches the highest values at the threshold range above 0.02. The normalized correlation between detected QRS segments (Fig. 8) is barely reaching 0.5 and was unable to help determine optimal threshold.

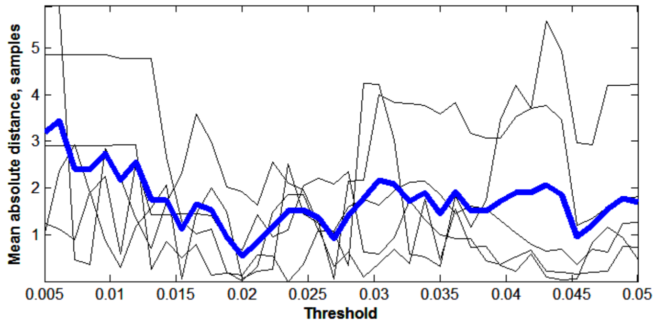

Fig. 3. Mean absolute R wave detection error for all records (thin lines) and the average of them (thick line) versus tested ECG quality algorithm threshold

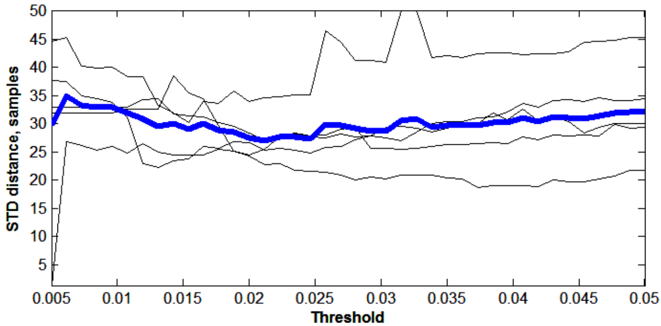

Fig. 4. Standard deviation of R wave detection error for all records (thin lines) and the average of them (thick line) versus tested ECG quality algorithm threshold

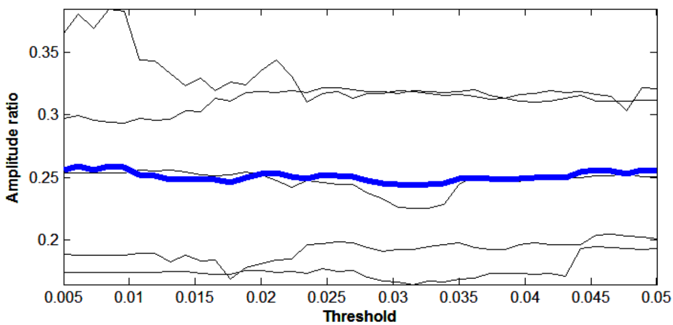

Fig. 5. R wave amplitude ratio for all records (thin lines) and the average of them (thick line) versus tested ECG quality algorithm threshold

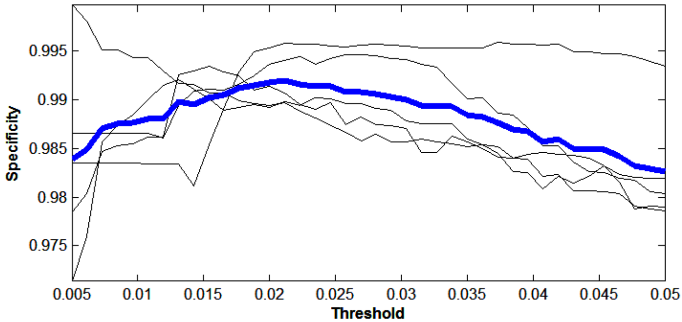

Fig. 6. Specificity of R wave detection for all records (thin lines) and the average of them (thick line) versus tested ECG quality algorithm threshold

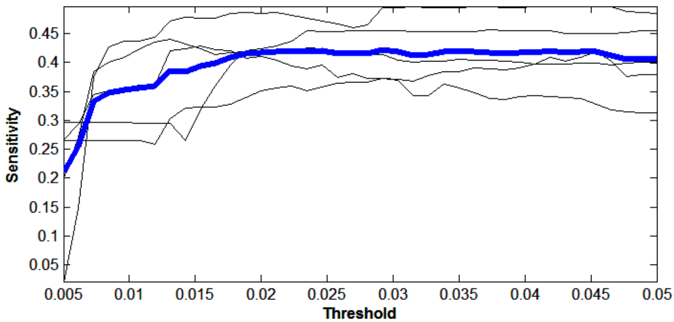

Fig. 7. Sensitivity of R wave detection for all records (thin lines) and the average of them (thick line) versus tested ECG quality algorithm threshold

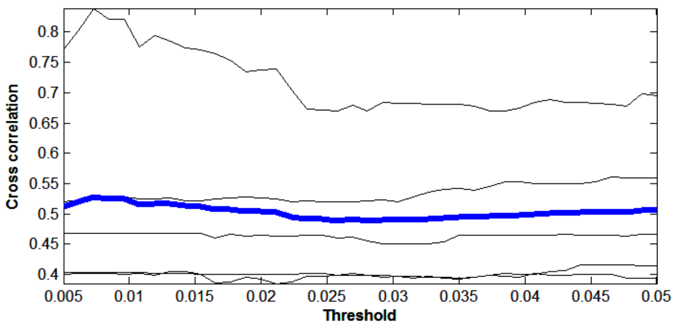

Fig. 8. Cross correlation of QRS complexes for all records (thin lines) and the average of them (thick line) versus tested ECG quality algorithm threshold

Conclusions. During this research a framework for testing performance of the algorithm which is able to measure signal quality of ECG recorded with two textile electrodes embedded in casual clothing was developed. Performance testing revealed that two of five tested parameters did not represent any optimal tendency adjusting algorithms' performance. Neither QRS complex correlation nor R wave amplitude ratio showed any statistical change in algorithm performance. Other three parameters: R wave detection error (mean absolute distance and distance standard deviation), sensitivity and specificity showed feasibility in ECG quality algorithm performance testing. Using tested algorithm R waves detection can be achieved with very high specificity (>0.99) and moderate mean sensitivity which can be improved by adapting clothing used with textile ECG electrodes for unique subject or application. Framework could be used to evaluate credibility of algorithm under test as well as finding optimum specific values to increase its performance.

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ECG quality detection algorithm is dealing with harsh and unstable ECG signal gathered from textile electrodes implemented in casual clothing. Since algorithm is able to reject noise contaminated signal its performance is very threshold dependent and there is no standard methodology to test this kind of algorithm. Proposed framework analyses ECG quality algorithm performance on various thresholds in terms of five parameters. Three of five tested parameters revealed feasibility in ECG quality algorithm performance testing. Results revealed certain threshold and conditions when algorithm is able to perform best as well as performance limitations.