A Software Tool for ECG Signals Analysis and Body Surface Potential Mapping

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Abstract— **This paper presents an overview of a software tool for preprocessing, analysis and visualization of ECG signal. The aim of this work is to automate the task of preprocessing, analysis, visualization, signal frequency decomposition, and map creation by multi-channel measurement from patient body surface (Body Surface Potential Mapping, BSPM). Signal frequency decomposition is performed by continuous wavelet transform. BSPM provides large amount of electrocardiological data for further processing. This software tool has been programmed in Java. The program has been tested on the data acquired from the CARDIAG 112.2 system, which measures signals from 80 unipolar electrodes evenly placed on the body surface.**

I. INTRODUCTION

THIS paper describes developed software tool for preprocessing, analysis, visualization and features extraction from ECG signal and Body Surface Potential Mapping (BSPM). Signal preprocessing and analysis are based on discrete wavelet transform. Visualization is represented in the form of maps created from multi-channel measurement from patient body surface.

We use analysis based on wavelet transform for detection of ECG characteristic points. These points are: maximum amplitude of R wave; beginning and maximum amplitude of Q wave; maximum amplitude and end of S wave; and beginning, maximum amplitude and end of P and T waves. In wavelet transform, we use for signal decomposition low and high pass quadrature FIR filters. Coefficients of impulse responses of filters are obtained from quadratic spline wave. However, the user may define one´s own wave, either as scaling function or as coefficients of low pass and high pass filters. We use four details for ECG analysis. Based on detected points, ten attributes are extracted. The user may choose signal or signals and period or periods for separation of these attributes.

One period of analyzed signals is always used for creating the maps. The basis of the map is a matrix of 16x5 points, starting from one position in all used signals, transformed into colored scale. The whole displayed matrix is interpolated by local Hermit interpolation. The mapping offers generation of four types of maps: immediate potential maps, integral maps, isochronic maps, and last type are differential maps. All maps can be displayed either in color scaling or bipolar range with draw contour.

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II. DISCRETE WAVELET TRANSFORM AND FIR FILTERS

The signal f(t) can be described by wavelet function $\varphi_k(t)$ and $\psi_{j,k}(t)$ by [1] as:

$$f(t) = \sum_{k=-\infty}^{\infty} c_k \varphi_k(t) + \sum_{j=0}^{\infty} \sum_{k=-\infty}^{\infty} d_{jk} \Psi_{jk}(t) \qquad (1.1)$$

where $\varphi_k(t)$ is scaling function, $\psi_{jk}(t)$ is wavelet function, c_k is called approximation and d_{jk} is called signal detail.

We have used filters bank (quadrature mirror filters) and Mallat's algorithm for discrete wavelet transform performing [2]. Basic form of Mallat's algorithms for

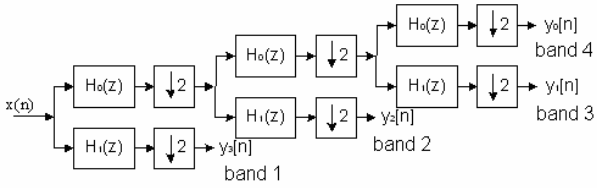

Fig. 1. Mallat's algorithm with FIR low and high pass filters for 3 levels.

decomposition with low pass and high pass FIR filters is shown in Figure 1. Partition of frequency band is shown in Figure 2. In the left column there are modulation characteristic of individual filters, in the right column there

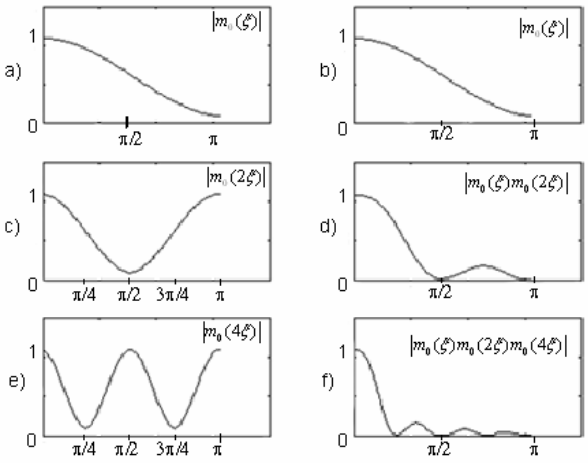

Fig. 2. Partition of frequency band on individual filters and their mutual convolutions

are modulation characteristics of impulse response convolution.

For filters in bank following assumptions must be valid:

$$\tilde{a}^0(z)a^0(-z)+\tilde{a}^1(z)a^1(-z)=0 \qquad (1.2)$$

$$a^1(z)=a^0(-z)$$

$$\tilde{a}^0(z)=a^0(z) \qquad (1.3)$$

$$\tilde{a}^1(z)=-a^0(-z)$$

From equation 1.3 results that we need only a^0 coefficients for all bank filters coefficients calculation. However we want to get coefficients of impulse response. Relation between the a coefficients and h, g coefficients is shown in Figure 3.

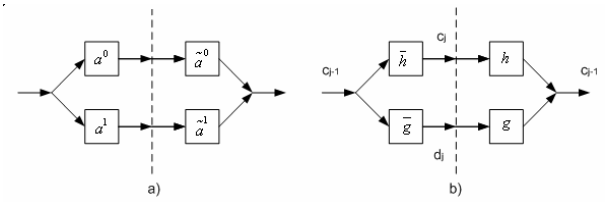

Fig. 3 Relation between coefficients of filters bank and coefficients of decomposition and reconstruction filters

So, it is valid by [1]:

$$h(z^{-1})=a^0(z), \text{ so } h(z)=\tilde{a}^0(z) \qquad (1.4)$$

Between low pass and high pass coefficients the relation holds:

$$g(L-1-n)=(-1)^n h(n), \text{ resp.}$$
$$g(n)=(-1)^n h(-n+1) \qquad (1.5)$$

From equation 1.5 we get coefficients for reconstruction filters. For decomposition filters the equation [1] is suitable:

$$\overline{h}(n)=\overline{h(-n)}, \text{ and } \overline{g}(n) = \overline{g(-n)} \qquad (1.6)$$

Reconstruction filter $g(n)$ is calculated as complement of filter $h(n)$, and decomposition filters $\overline{h}(n), \overline{g}(n)$ are defined as time reverse sequence of $h(n), g(n)$ filters.

III. Analysis

There are defined eleven characteristic points on one ECG period (maximum amplitude of R wave, beginning and maximum amplitude of Q wave, maximum amplitude and end of S wave, and beginning, maximum amplitude and end of P and T waves), whose localization is shown in Figure 4a.

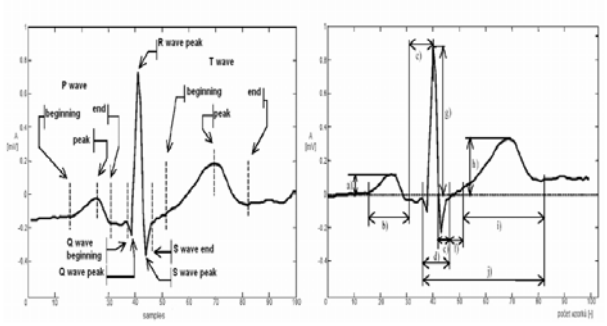

Fig. 4. a) Characteristic points on one period, b) ten defined attributes

Ten attributes are calculated on basis of location characteristic points, see Figure 4b. These attributes are [3]:

a) P peak - maximum P wave amplitude;
b) P wave interval – from P wave onset to P wave offset;
c) PR interval – from P wave onset to R wave maximum amplitude;
d) QRS complex interval - from Q wave onset to S wave offset;
e) S interval - from S wave offset to S wave offset;
f) ST interval - from S wave offset to T wave onset;
h) T peak - maximum of T wave amplitude;
g) R peak - maximum of R wave amplitude;
i) T wave interval - from T wave onset to T wave offset;
j) QT interval - from P wave onset to P wave offset.

The characteristic points are found on decomposition signal by discrete wavelet transform [4]. The transform has four levels and quadratic spline as wavelet. First R wave maximum as zero crossing on all details is found. Then Q onset, Q peak, S peak and S offset based on position R wave as zero crossing and maxima in defined time window on 1st detail are localized. Final step is localization of P and T waves onsets, peaks and offsets. They are detected similarly as Q and S waves parameters, but on 4th detail. This process is displayed in Figure 5.

IV. Mapping

For observation of body surface potentials there are used

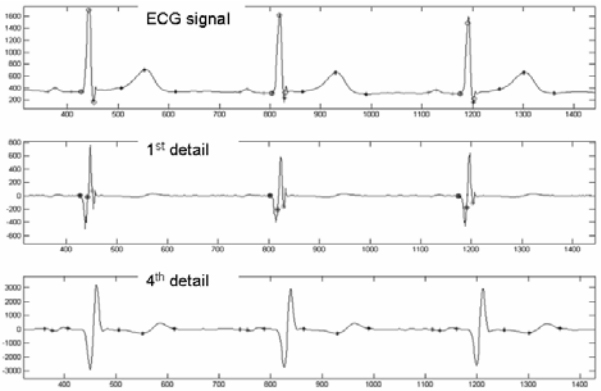

Fig. 5. Principle of detection characteristic points on 1st and 4th details from wavelet transform decomposition

multi-leads read system with 32 to 512 electrodes. In our application system CARDIAG 112.2 with 80 electrodes has been used. Examples of distribution of electrodes and measurement are shown in Figures 6a, 6b.

Four types of maps are defined in [6],[7]. First type is immediate potential map, which is created from current potential distribution on singles electrodes in the given moment. It is defined as:

$$P_i=U_i(t),\ t=const.,\ i=1,2,...,n \qquad (1.7)$$

Second type is integral map defined as

$$P_i=\int_{t_1}^{t_2} U_i(t)dt \qquad (1.8)$$

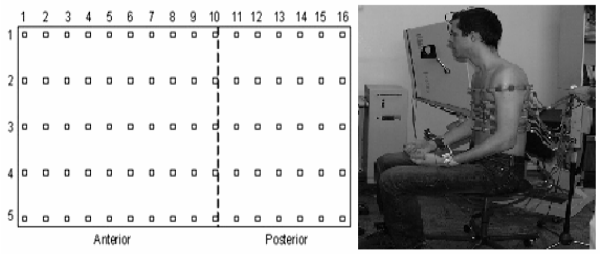

Fig. 6. a) Distribution of electrodes by body surface potential measurement, b) example of measurment

This map is generated as sum in chosen time interval $<t_1,t_2>$. User can choose interval for mapping arbitrarily. However, five intervals in application are predefined, which are chosen based on characteristic points from automatic analysis – P wave integral map, Q zone integral map, QRS integral map, ST-T interval integral map and QRST interval integral map. Third type is isochronic map, in which time of detection of some characteristic points on each signal or length of some defined interval is mapped. It is defined as:

$$T_i = f(U_i(t)) \tag{1.9}$$

Last type of map is differential map. It is created as subtraction of two integral maps. Again the user can choose interval for mapping and also has five integral intervals from automatic analysis, which is described above.
Differential maps are defined as:

$$\begin{aligned} D_i &= U_2(t) - U_1(t), \text{ resp.} \\ D_i &= P_2 - P_1 \end{aligned} \tag{1.10}$$

V. Final Application

A. Main window

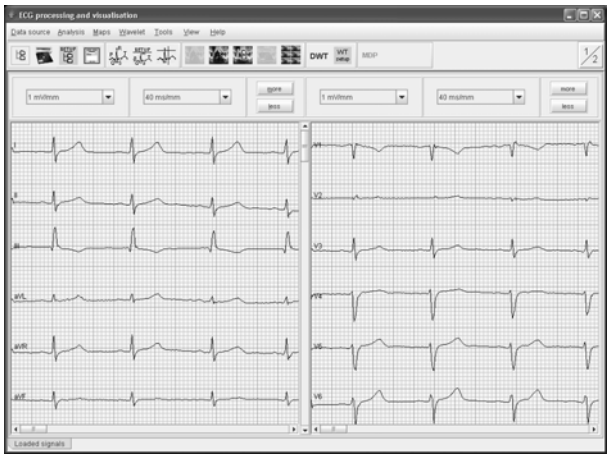

Fig. 7. Main window of ECG view and analysis tool

Main window is used for standard display ECG signals and their analysis (see Figure 7). It is possible to set up various time and amplitude scale. The user can set up basic parameters as order of file, delimiter sign, signals sample frequency and/or names of individual signals.

B. Wavelet transform

For preview of signal decomposition by wavelet transform, the window with switches for switching between approximates and details of signal decomposition is used. Example of this window for approximation and details is shown in Figure 8. Both decompositions are generated from the transform with spline wavelet.

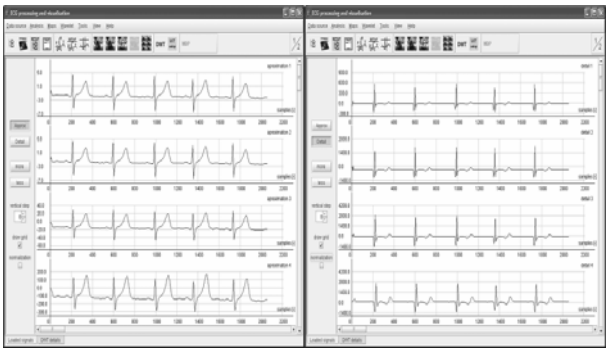

Fig. 8 a) Example of four approximates, b) example of four details

Selectable parameters are type of wavelet, order of wavelet and number of decomposition levels. There are predefined four types of wavelets (Daubechies waves from 1 to 10 order, coiflets waves from 1 to 5 order, biorthogonal waves from 1.1 to 3.9 order and quadratic spline. The user can define other wavelets either as coefficients of scaling functions or as coefficients of low pass and high pass filters.

Continuous wavelet transform is used only to display time-frequency distribution in chosen interval of signal. Figure 9 shows distribution of frequency a) before baseline correction, b) after baseline correction. Horizontal axis is time, vertical axis is frequency in logarithmic scale (bottom is low frequency).

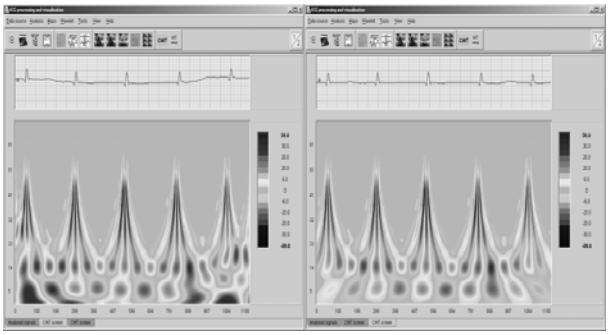

Fig. 9. Example of two result continuous wavelet transform- before and after baseline correction in Fourier spectrum.

There is used Morlet wave for decomposition to 60 levels. This wave is defined in Fourier transform as:

$$\Phi(\omega,\omega_0) = e^{-(\omega-\omega_0)^2/2} - e^{-(\omega^2-\omega_0^2)/2} \tag{1.11}$$

C. Analysis – characteristic point detection

There are adjustable four thresholds for R peak detection and one threshold for each remaining wave. The attributes are calculated as average from all periods of signal as a standard, however the user can specify, from which periods

and on which signals the attributes will be calculated.

In the main window the signal analysis is marked as color interval of P wave, QRS complex and T waves. Example of display analysis in the main window is shown in Figure 10.

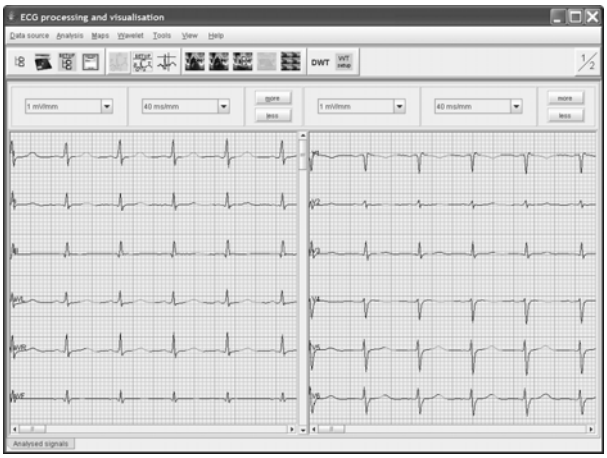

Fig. 10. Signal analysis mark in basic frame

For detailed display of analysis there is created a special window, in which individual detected points are shown. Figure 11 shows detailed location of P and Q wave onsets, R peaks and T wave peaks and offsets.

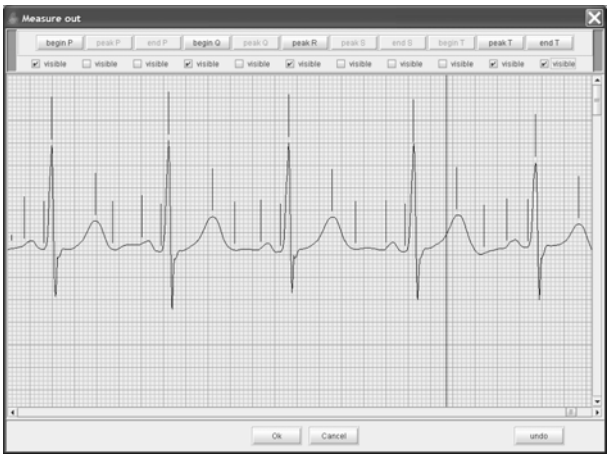

Fig. 11. Detail analysis display for P and Q wave onsets, R peaks and T waves peaks and offsets.

D. Mapping

Mapping module has three basic parameters:

- number of lead signal, which defines interval of one period;
- number of mapped period, because mapping is performed always on one period;
- first mapping signal.

Mapping on one period of signal, based on lead signal, turned out to be fundamental for the best display of immediate potential maps and integral maps. The mapped interval for generation of maps is defined unambiguously for all electrodes. Thus, it allows better variability of creating maps by user's choice from different periods.

Figures 12 to 15 show examples of individual map types.

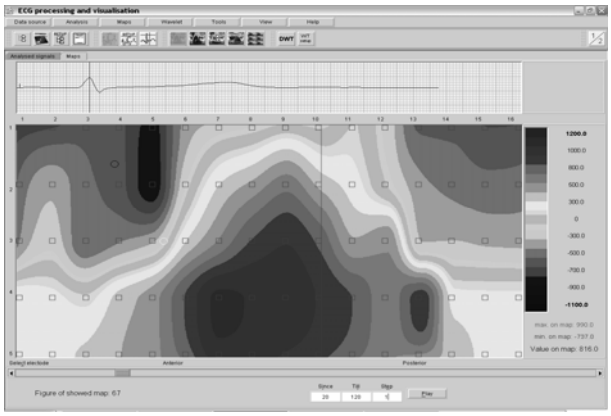

Fig. 12. Example of immediate potential map from QRS complex

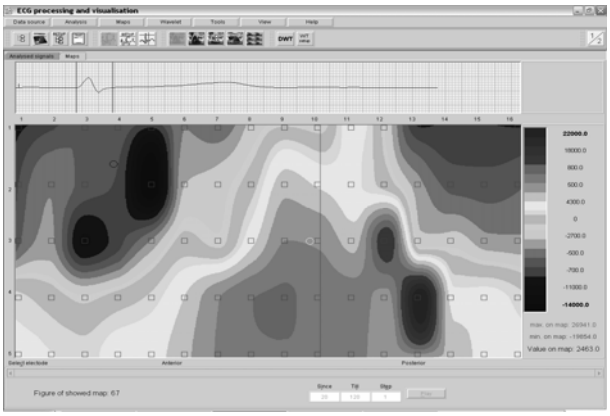

Fig. 13. Example of integral map from QRS complex

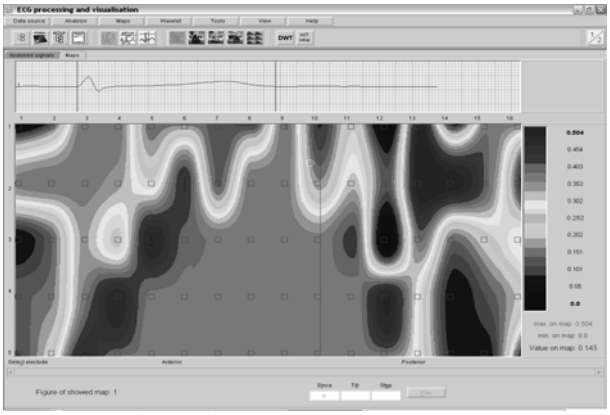

Fig. 14 . Example of isochronic map from QRS complex

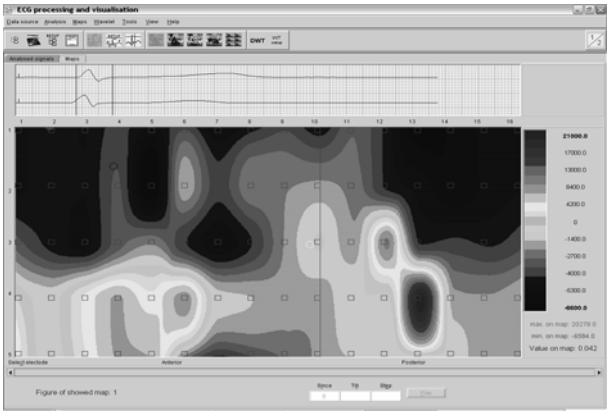

Fig. 15 . Example of differential map from QRS complex

VI. Conclusion and Discussion

Goal of this paper has been the description of the software tool for analysis of ECG signals and body surface potential mapping that has been designed, developed, implemented, and tested on real data. For preprocessing there is used the wavelet transform. Based on it, analysis and subsequently attribute extraction and map generation are defined. The application is independent on computer operation system, because it is programmed in Java.

The software tool offers 2-dimensional visualization of body surface potential maps. If we want to perform mapping on 3D models, we would have to solve the problems of heart geometry and position and legitimacy of the 3D model used.

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