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NOISE-REDUCTION AND DATA-COMPRESSING OF BSPM-SIGNALS WITH THE HELP OF SYNCHRONIZED AVERAGING[1]

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Abstract

As a part of our effort in the development of a high-resolution body surface potential mapping (BSPM) system, we have developed a new software for data acquisition and processing. With the help of the BSPM technique we are able to extend the applicability of electrocardiography.

The new signal processing steps developed improve signal-to-noise ratio (SNR) and compress BSPM signals. During our work the utility of the simultaneous perturbation stochastic approximation method (SPSA) was tested. The method was used for the high-precision classification of QRS patterns, prior to synchronized averaging.

Keywords: ECG, high-resolution, BSPM, classification, SPSA, synchronized averaging.

1. The Definition of ECG Signal and its Intervals – Introduction

The mechanical activity of the heart is preceded by an electric activity, which can be measured noninvasely with the help of electrodes on the surface of the body. This is the ECG signal [4]. *P-wave* of the ECG signal coincides with the propagation of the atrial depolarisation. The *Q*-, *R*-, and *S-waves* (the *QRS-complex*) represent the propagation of ventricular stimulus. In the meantime the atrial repolarisation takes place too, but the amplitude of the *R*-wave is so high, that it completely covers the repolarisation wave with a much smaller amplitude. *T-wave* is the period of ventricular repolarisation. Sometimes the *T*-wave is followed by a *U-wave* with a small amplitude, its origin is not yet known. It is interesting about this wave that it is more often to be observed in ECG records of women.

2. Aim

Our final-goal is to elaborate a signal processing, visualisation and decision-support system, with the help of the latest measurement technique and original signal processing methods, which helps the work of cardiologists.

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3. The Differences between ECG and BSPM Signals

The signals of the ECG are projections of a rather complicated three dimensional electrical process. The ECG has more types: unipolar or bipolar leads, VCG (vectorcardiagramm: it represents the electrical potential-changing of the heart as a vector, and it shows the rotation of this vector in time), etc. All types of conventional ECG interpretation is based on Einthoven's Dipol theory (according to this theory the electrical activity of the heart can be characterized by a current dipole-model). There are several types of arranging the measuring leads: 3 leads of Einthoven, Simpson leads, etc. Although there are many types of ECG, all of them mean an under-sampling in the spatial domain.

Fig. 1. Data-acquisition nowadays: with the help of a BSPM system

With the help of BSPM we are able to obtain an adequate spatial sampling. We can improve the spatial sampling rate by increasing the number of leads/channels. These are only matter of hardware – but are not cheap.

In *Figs. 2* and *3*, the differences between the two visualization methods of the two data-acquisition methods are visible. The ECG is only a simple time function (two dimensional). A time instant BSPM is a two dimensional instantaneous map (there is no time function!), the time course of electrical activity can be represented by a series of time parameterised maps. There are several visualisation methods of BSPM: contour plot, three-dimensional surface map – the last one is not so usual. A really good BSPM system is able to draw a map and a few reference ECG signals too.

Of course, we can draw a map in animated form (e.g. generated in MatLab) too. The animation is rather scenic, but for human analysis is not the best. It is a well-known fact that the resolution of the human eye is good at still images, but for a movie-like motion picture is worse.

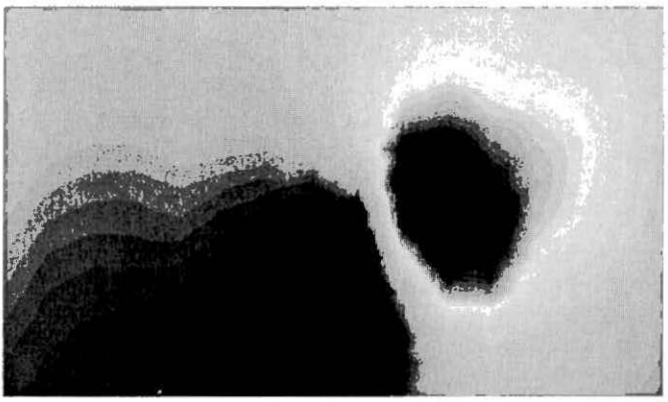

Fig. 2. Colour coded instantaneous BSPM

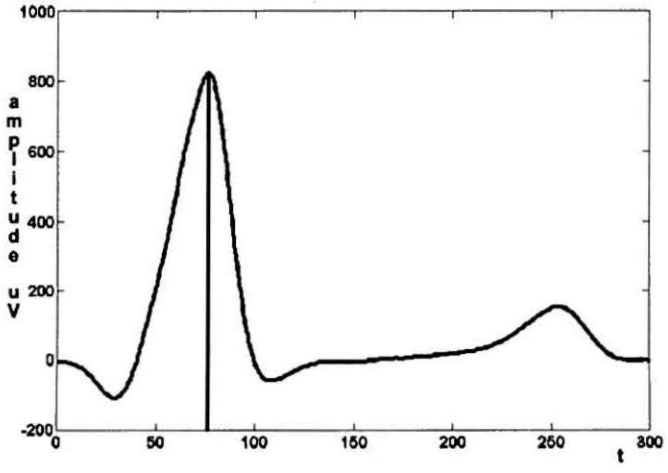

Fig. 3. The time function of a simple ECG channel

The map in *Fig. 2* was drawn by a 192-channel system, where the distribution of the electrodes was equidistant. In our system we use the same mesh-grid, but the distribution of the electrodes is not equidistant: the electrodes are closer to each other in the precordial area than at other locations. Therefore we have to use interpolation or matrix transformation before drawing maps!

4. Options

We are elaborating a new, high-resolution mapping method, because the diagnostic importance of a signal in the ECG/BSPM is not proportional with its amplitude [5].

The amplitudes of signals, which we are looking for, are in the domain of μV-s.

Our options to improve the signal-to-noise ratio (SNR) are the follows:

- First to reduce the under-sampling with the help of a high-channel data-acquisition technique. We use a Biosemi Mark-8 quad, which is a modern BPSM data-acquisition instrument. It has sixty-four channels , the time domain sample rate is 2048 Hz.
- Our second goal is to improve the signal-to-noise ratio (SNR). Here we have to elaborate new signal processing method(s) to remove noise from the BSPM signal. Afterwards we need to apply new visualization methods for the improved quality signals. It is not a matter of hardware anymore, it is a matter of software, programming.

5. Signal Processing Method

The goal of signal processing is, on the one hand, the improvement of the signal-to-noise ratio, and on the other hand the data-compressing.

One option to improve the signal-to-noise ratio is filtering. Unfortunately, the filter eliminates not only the noise but the useful signal components too in the frequency domain. This can not be allowed, because we want to recover even the fine details of the signals in the amplitude-range of μV-s.

So we have to use synchronized averaging to improve the signal-to-noise ratio.

Synchronisation is important, because the activity of the heart is not periodical, only quasi-periodical. Averaging is reducing the random noise (white-noise or band-limited random noise). Averaging is also a data-compressing method in the BSPM technique: after a longer data acquisition we need to store only an averaged cycle.

But it is an important question: which cycles could be included in the process of averaging? The inclusion of a 'bad' cycle (e.g. an extrasystole) damages the SNR in the averaged cycle too.

It means that we have to classify the cycles.

The segmentation of the individual cycles before synchronizing and classifying them uses the wave characters of the QRS complexes and it is based on [2] and [6].

5.1. Classification

5.1.1. The Method of Correlation Coefficients

This method chooses a reference cycle (e.g. a pre-average cycle – it means that all the cycles were included into the averaging without classification), and calculates

the correlation coefficient between the reference cycle and the other cycles. After then it applies a threshold value (international recommendations [1] offer 0.98; or we can calculate one by the mean value of the correlation coefficients). If a correlation coefficient is lower than the applied threshold, then the method drops the cycle and will not include in the averaging.

5.1.2. The Simultaneous Perturbation Stochastic Approximation (SPSA or min-max) Method

This is a modified version of SPSA method to classify ECG cycles [7], [3]. This method handles the cycles as points. In the 3D space, if we want to describe a point, we need 3 numbers (co-ordinates) to define the location of the point. A cycle consists of n sample points, and has m channels. So n times $m = N$ numbers describe a cycle, so a cycle is a point of the N dimensional space. The SPSA method chooses two spheres to cover the points/cycles, and tries to minimize the radius of the spheres, of course, modifies the centre of the spheres, too.

5.1.3. The Differences between the two Classifying Methods

For comparison, we use two records (see *Figs. 4* and *5*). These figures contain only the 3 leads of Simpson and are under-sampled for better and easier visualisation. The first record is an 'excellent' sample, (all cycles are very similar), while the second record contains five ventricular extra beats. There is a time window around the fiducial point, lead by lead, with a length of 66 ms.

For the min-max criterion, the signals obtained during the time windows of the three leads are concatenated. Thus, a single cycle will be represented by $3 \times 66 = 198$ sampling points, i.e., one cycle is a point of the 198-dimensional space. These strings are shown in *Figs. 4* and *5*.

In the correlation method, first a reference cycle is calculated for all the time windows lead by lead. Subsequently, the cycles are compared: if a cycle on one of the leads has a correlation coefficient smaller than 0.98, we drop that cycle from all three leads. The threshold value 0.98 meets the international standards.

In *Fig. 6* the ECG-record of *Fig. 4* is analyzed. The correlation coefficient of each cycle is above 0.98, hence, no cycle will be qualified as an outlier [1]. On the other hand, the homogeneity of the record can be improved using min-max classification with two classes, and removing the data belonging to the class containing less samples. The deleted data points are marked by *.

In *Fig. 7*, the ECG record in *Fig. 5*, containing five extra beats, represented by dotted lines, is analyzed. The correlation method detects these extra beats, but no other cycles are deleted.

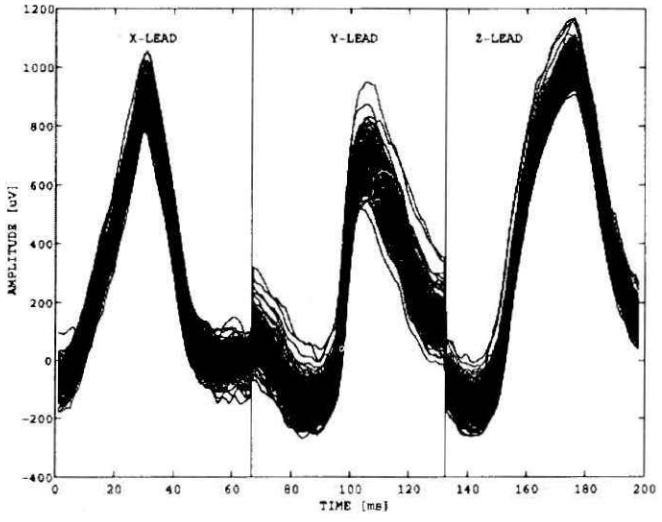

Fig. 4. Superimposed cycles of a typical ECG record for comparison

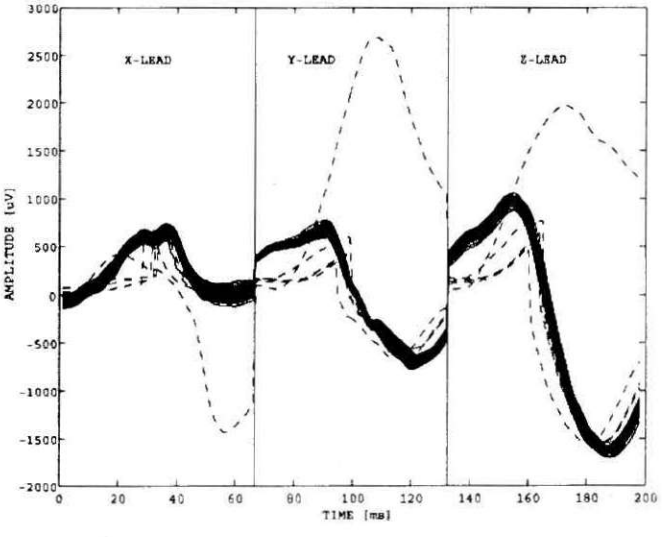

Fig. 5. Superimposed cycles of an ECG record with some extra beats, used for comparison

To get a more homogeneous record, we apply min-max classification with two classes on these preclassified data, as in the previous experiment. An interesting feature of this procedure is that the most of the cycles that closely precede or follow

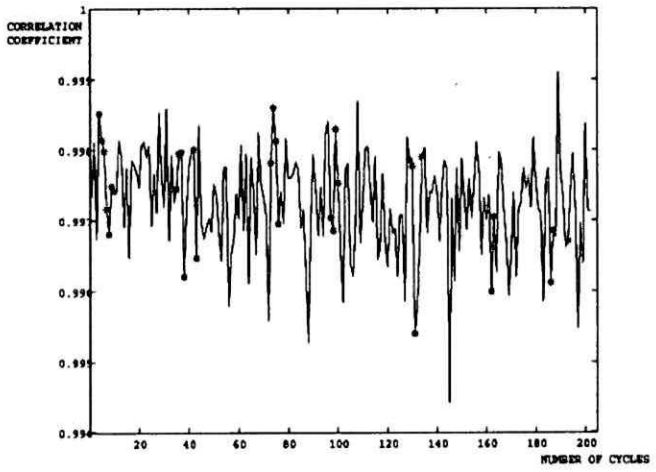

Fig. 6. Correlation coefficients of the first ECG record; the signals marked with * were deleted by the SPSA method

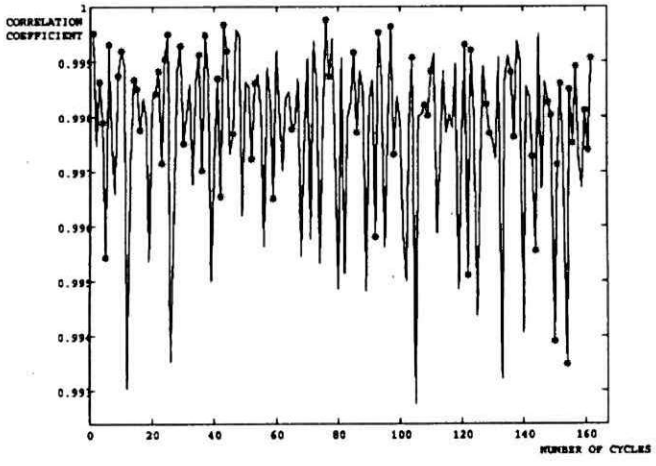

Fig. 7. Correlation coefficients of the second, preclassified ECG record; the signals marked with * were deleted by the SPSA method

the extra beats have been automatically deleted, although these extra beats are not present in the preclassified data set. This is in agreement with the common practice that the mentioned cycles are deleted manually when the correlation method is applied.

The conclusion of *Figs. 6* and *7* is that the set of QRS complexes that are similar in terms of the correlation method coefficients may eventually be separated by the SPSA method. A careful comparison using synchronized averages and second derivatives results in two representative signals that are slightly shifted and also different in fine details of their pattern. The biophysical background of the second derivatives suggests that pattern changes might be due to slight differences in local intraventricular activation propagation velocities, causing shifts in the timing of collisions of activation wavelets originated in distinct points of the Purkinje fiber-endocardial interface. We have to emphasize that the above interpretation needs further confirmation, though previous numerical modelling studies support our hypothesis [5].

These findings indicate that min-max classification may give a useful complementary insight to detect minor morphological differences. An advantage of the min-max method is that it allows the user to assign different weights to different coordinates, or even morphological parameters. Different coordinates may carry different biomedical content based on the expertise of cardiologists. Tuning these weights is an additional degree of freedom in the hands of the cardiologist to detect specific abnormalities.

5.2. Data Storage

After reading the sample points, we convert them to a 3D matrix. The first and second dimensions mean the location of the electrodes (row, column) – of course, the question of interpolation/transformation appears here, too. The third dimension means the time axis. One grid on the time axis means one sample point. So one 'slice' of the 3 dimensional matrix means one map. And at the position of one electrode along the time-axis, we can find a 'conventional' ECG sample. So with this data storage we are 'compatible' with the previous system. It is very important in the interpretation of the new results.

6. Goals and Further Plans

We have elaborated the waveform analysis of the ECG signals (QRS detection), the classification of the individual ECG cycles, the time-aligned (synchronized) averaging of the cycles of the main class of the ECG cycles – in the meantime the improvement of the SNR in the ECG signals without any filtering.

We have developed the main visualisation methods (both for still images and motion pictures) for BSPM systems, where the distribution of the electrodes is equidistance. These steps were elaborated in MatLab and NI LabVIEW environment.

Our further plans are the hardware programming for Biosemi Mark–8 data acquisition instrument, in the meantime the development of the real-time signal

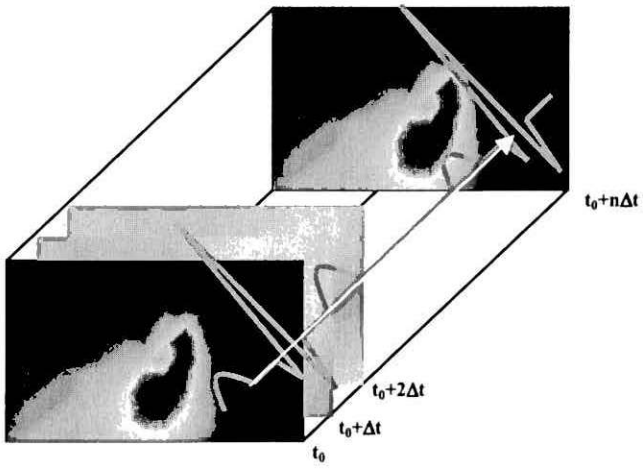

Fig. 8. The data storage of the BSPM signals in 3D matrix form

processing software and the storing of the acquired data. After then we would like to use it for clinical data acquisition, then to create a database validated by ECG-independent evidences.

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