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Computer analysis of multichannel ECG

Roman Trobec*

Department for Communications and Computer Networks, Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia

Abstract

Multichannel electrocardiography (MECG) is an extension of the conventional electrocardiography that is aimed at refining the non-invasive characterisation of cardiac activity. Body surface mapping is a graphical presentation of cardiac activity as measured from the body surface. Body surface maps can show the distribution of the potential at a selected moment in time or over a specified time interval. A new family of maps, based on the characteristics derived from the complete analysed beat, is described. Some new computer supported methods, which are able to calculate automatically different temporal maps, are proposed. MECG measurements can be seen in this context as a powerful research and clinical tool for improving the resolution of cardiac measurements.

Keywords: Multichannel electrocardiography; Body surface mapping; Isopotential maps; Isointegral maps; Temporal maps; Amplitude maps

1. Introduction

Multichannel electrocardiography (MECG), an extension of the conventional electrocardiography that is aimed at refining the non-invasive characterisation of cardiac activity, has been used in body surface mapping (BSM). Increased spatial sampling on the body surface provides more in-depth information on the cardiac generated potentials [1]. Graphical presentation of the potential or integral BSM can be a useful tool for personal or statistical analysis of different heart diseases. Well-known body surface maps can be identified as isopotential, giving a distribution of the potential at a specific moment, and isointegral, providing a distribution of the sum of potentials over a specified time interval (QRS, ST40, etc.).

Different MECG systems have been used for BSM, with the number of electrodes ranging from 10 to 300 [2,3]. It has been shown that a reduced set of about 30 electrodes can monitor almost all the

* Tel.: +386-1-477 3497 Fax: +386-61-426 2102.
E-mail address: roman.trobec@ijs.si (R. Trobec).

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information on heart activity that can be detected at the body surface [3]. The result of an MECG measurement is in fact a series of consecutive vectors in time, encapsulating data collected by all the electrodes at the sample time. These vectors can be visualised using interpolation, by different types of isovalued lines or regions, also called the body surface map. Electrodes that can or must be placed at different positions result in different data, so that some kind of data transformation has to be performed to obtain normalised and comparable results [4,5]. Measurements can be performed for time intervals from several minutes to several hours, the limiting factor being the computer memory required.

Different types of maps have been generated in the past, either well established isopotential maps and isointegral maps [6], estimating the selected time point of an analysed beat or the average beat. Some effort has also been concentrated on generating more sophisticated isochronal maps [7]. Temporal maps are based on the automated measurement of time for different characteristic points in the analysed beat signal, like the time of the R-wave or T-wave peaks or the time of maximal declination in a beat, particularly in connection with endocardial measurements [8,9]. Frequently, maps taken at different times or from different persons have to be compared objectively in order to quantify the similarities between them. The correlation coefficient and the root-mean-square of map differences have proved to be excellent methods for such purposes.

In this paper, a more formal definition of BSM is introduced and used for presenting well known isopotential and isointegral BSM. Then, a new family of maps, based on the characteristics devised from the complete, analysed beat is introduced. Further, some new computer supported methods, able to calculate automatically the isotemporal BSM, are presented. Based on the temporal analysis we can search for the moment when a specific action in the heart starts and, at the same time, for the place where it originates. We can follow the development of this action very close, at least, to its start [10,11]. Such maps are sometimes called activation isotemporal maps. With the consecutive application of the isotemporal algorithm to two waves, wave-to-wave variability (i.e. QT-variability) can be analysed. The MECG measurements constitute, in this context, a powerful research tool, because the redundant data can now be used to validate findings, particularly in cases where the results are not obvious. This is the case, for example, if signals from some electrodes are noisy, or if we search for possible spatial variability of some heart parameter [12,13].

In the next Section, an MECG measuring system is presented, with an example of the isopotential BSM. In Section 3 a more formal presentation of MECG measurements and BSM is introduced. Different types of BSM are identified and the procedures for generating these maps are described. In the last section, new concepts of the non-standard use of MECG measurements are analysed, taking into account technological advances in the area of computer science and communication. In particular, some new possibilities for generating and presenting body surface maps, based on amplitude or time measurements, are given. In the Conclusion, MECG measurement and BSM is discussed from the clinical and research perspectives.

2. MECG measuring system

2.1. Equipment

Body surface potentials were measured with 35 unipolar leads referenced to the Wilson central terminal. We measured potentials from 32 electrodes placed on the thorax and an additional three

electrodes placed, one on each arm and the left leg. The right leg electrode (electrode 0) was used for a ground reference and not measured. We used the MECG measurement system that comprises a small battery-powered acquisition unit and a PC-computer running the application software with built-in self-testing capability (for details see [14]).

The software package of the system is designed to be used by a normally trained user with no specialised knowledge of computer science. The raw data can be shown, analysed, and presented graphically in a time domain as standard ECG plots, different body surface maps or as animated maps. Beat rate can be found automatically, by different algorithms, and its frequency spectra can be calculated and shown. QT-variability can be also studied independently for each channel. Additionally, there is the possibility of performing several operations on raw signals (base-line correction, filtering, averaging, integration, differentiation, scaling, etc.). The computer program enables an MECG measurement to be loaded from a computer file into the computer memory, to show and analyse measured signals. Signals can be examined manually interval-by-interval and the most appropriate beat or measurement interval can be selected for analysis. In order to improve reliability, several consecutive beats can be averaged and this average beat analysed further. All data presented in this work are taken from a single patient operated by partial left ventriculectomy [15], but the proposed methods were tested on more than 300 patients and volunteers. The complete software package was implemented at the Jožef Stefan Institute and the Clinical Centre Ljubljana as a custom designed version for research use (Fig. 1).

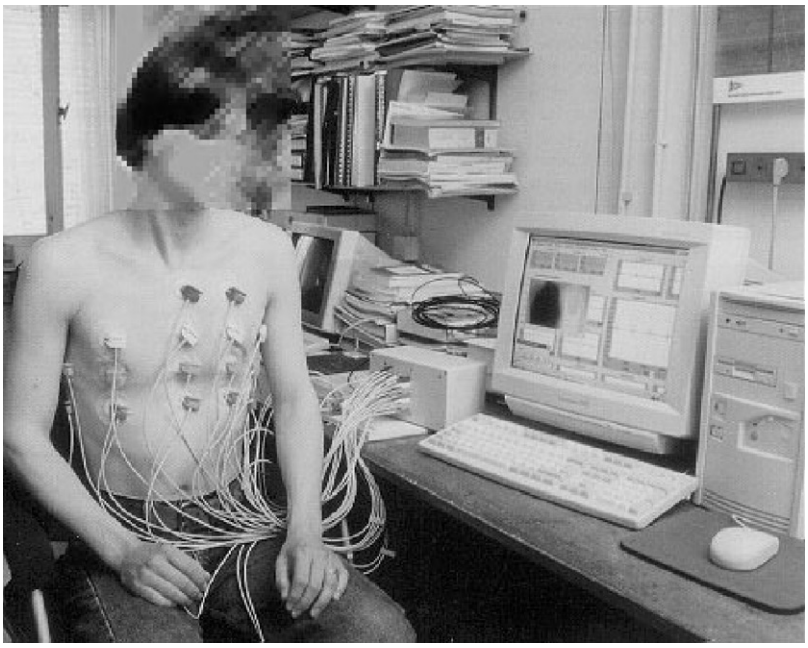
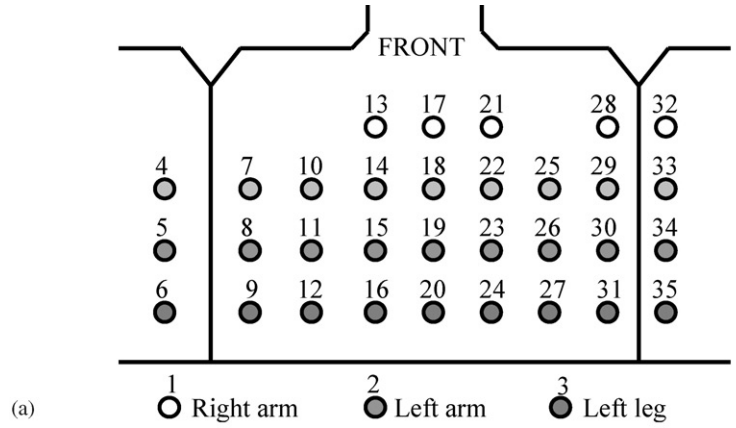


Fig. 1. 35-channel MECG measuring system.



(a)

(b)

Fig. 2. (a) The positioning and numbering of 35 electrodes arranged by equidistant placing and adapted for patients soon after a heart surgery. Colour codes are presented in different levels of grey and (b) actual MECG signals shown for all channels for the first three seconds of a 35-channel measurement.

2.2. Placing electrodes

Different positioning is possible, but equidistant positioning of electrodes gives immediate results and all further analysis can be performed on the originally measured data. The reduced set of electrodes, based on the maximal information criteria proposed in [3], is an obvious advantage, but an additional transformation of data has to be applied to correctly reproduce approximated equidistant maps. If such a transformation were to be standardised, then the best choice would be the reduced set, but for users who want immediate results a better alternative is an equidistant placing (Fig. 2).

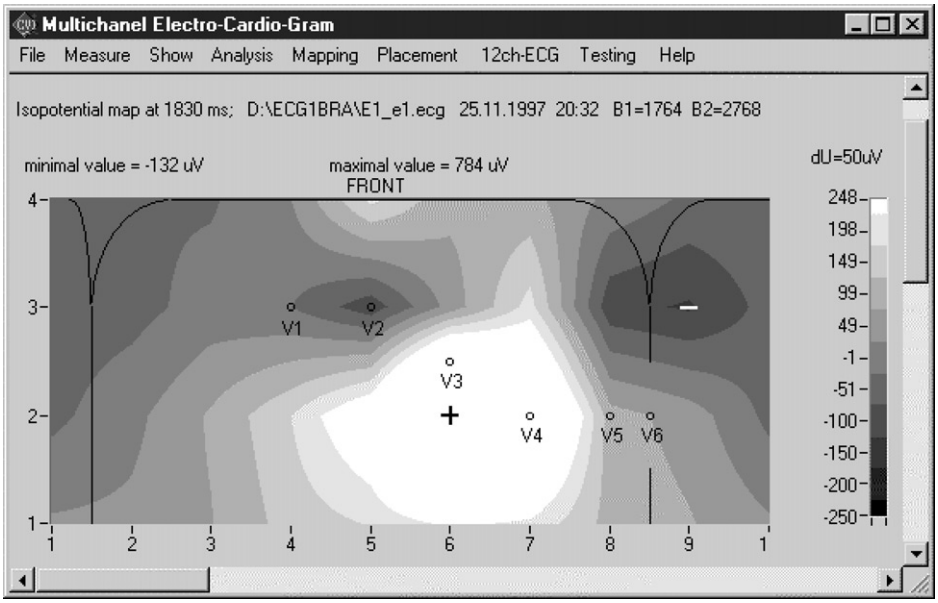


Fig. 3. An example of the isopotential BSM, taken from a preoperative measurement. It shows the moment 30 ms after the start of the heart activity, defined by the earliest onset of the Q-wave. Each different level of grey presents 50 μV of change, as shown on the right bar. The rectangular area represents the unfolded surface of the human torso from sternal notch (5,4) towards the umbilicus (5,1) by 4 lines of electrodes, numbered from 1 to 4, placed in nine columns, numbered 1 to 9. The first left column 1 is the same as the last right column 1 for easier readability. Schematic FRONT and part of BACK part of the body is shown with left and right axillary mid. V1–V6 are shown as the reference points.

2.3. An example of isopotential BSM

For each sample time, a rectangular area called the isopotential BSM, can be generated as shown in Fig. 3. It represents an approximation of the unfolded body surface with corresponding electrodes. The particular BSM consists of a mesh of four rows and nine columns. The electrode positions are in the mesh of the row–column crossing points, for example electrode (1,1) is the lower left electrode. Exact measured values are given only on these locations, while the rest of the map area is filled by interpolated values. The range shown is given on the right range bar and is represented by different colours or different levels of grey. The maximal and minimal values of a particular map are given in the first line above the map. The position of the maximal and minimal values are denoted by + and − signs, respectively. The map type, file data, time and other specific values needed for reproducing the map are given in the heading lines.

3. Definition of body surface maps

A multichannel measurement is performed in such a way that all N channels are sampled at the same time with a sampling rate of S samples per second. A typical value of S is 1000 samples/s. It is customary to express the elapsed time or time interval t in terms of the number of samples. For

example, ST40 represents an interval $t = 40$ ms after the J-point. For a particular sample rate S we should therefore analyse k consecutive samples, where

$$k = tS = 40 \text{ samples.}$$

The total number of samples K obtained during the measuring time T, can be expressed now as $K = TS$.

Any single-channel measurement can be represented as a set of consecutive samples x_j, where j is the index of an actual sample and runs from the first sample to the final sample of the measurement: $j = 1,\ldots,K$. The samples from all N channels can be encapsulated into an N-vector $\mathbf{x}_j$ that holds the measured values from all electrodes of the same sample, where its element $x_{j,i}$, $i = 1,\ldots,N$, is the measured value at sample j from channel i.

3.1. Isopotential BSM

The vector of simultaneous measurements from all channels $\mathbf{x}$ is the basis for a body surface potential map PM. In fact, after a spatial distribution and an eventual correction followed by an interpolation in two dimensions, the isovalued contour lines constitute an isopotential body surface map

$$\text{PM} = \mathbf{x}_j$$

at sampling time j.

3.2. Isointegral BSM

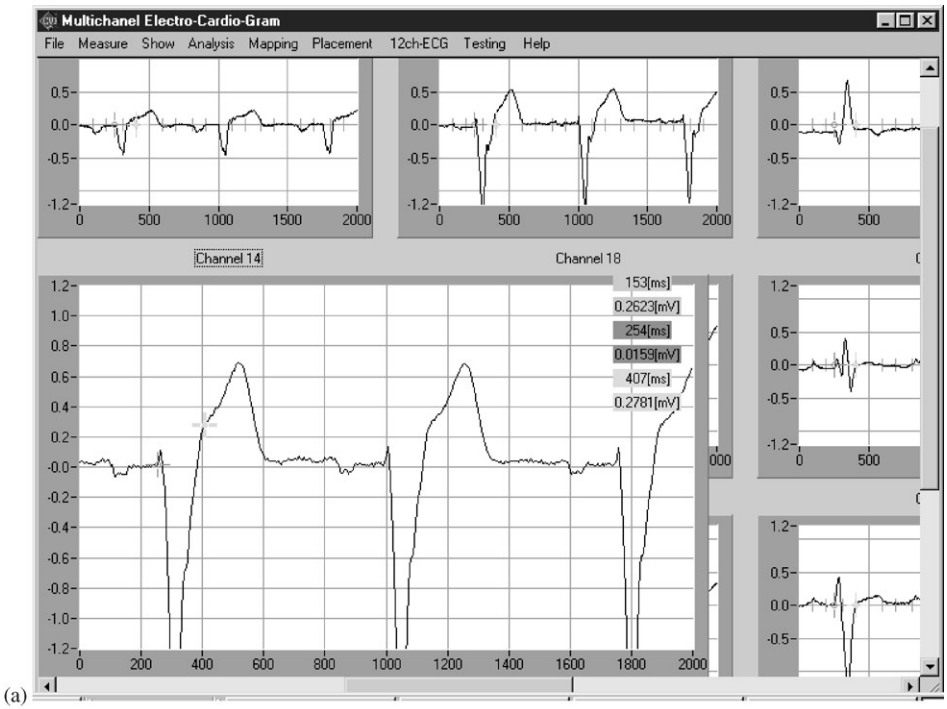
The sum of measured potentials over a specified interval constitutes an isointegral map IM. Each value on such a map is the sum of all sampled values $\mathbf{x}_j$ during the specified time interval $t = t_2 - t_1$. The IM is given by

$$\text{IM} = \sum_{j=j_1}^{j_1+k} \mathbf{x}_j r,$$

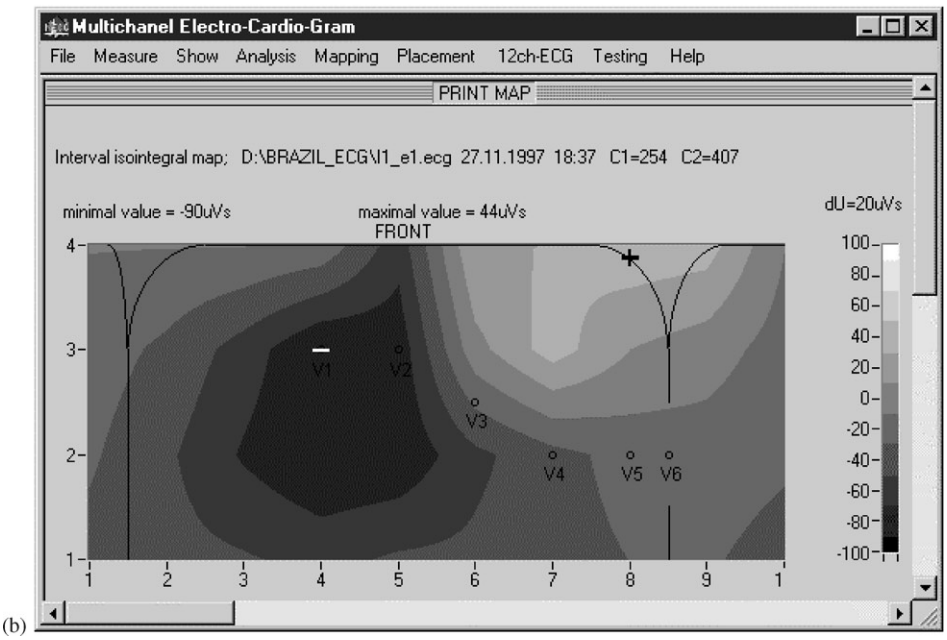
where r is the sample time in seconds, equal to the reciprocal value of the sampling rate $r = 1/S$, and $k = tr$ is the number of samples to be integrated. The starting sample is denoted by j_1, where $j_1 = t_1 r$. Time intervals can be selected in different ways. Well established intervals are ST40, QRS duration, QT time, etc. The units of each value on an isointegral map are Vs (volt seconds). These maps constitute in fact a concentrate of information of the heart activity during the selected time interval. In Fig. 4, the method for obtaining an IM is illustrated for $t =$ interval of QRS.

3.3. Normalised beat amplitude maps

The normalised beat amplitude is the sum of absolute values of amplitudes from a selected beat defined by two cursors, calculated for all channels. It can be normalised by the average channel beat amplitude A, that is, the sum of amplitudes from all channels divided by the number of channels



(a)



(b)

Fig. 4. (a) The procedure for generating an isointegral BSM: filtering and base-line correction were already performed; the interval of integration is determined by two cross-cursors and (b) the resulting QRS isointegral body surface map IM has minimal and maximal values of -90 and 44 μVs, respectively.

N. The corresponding map AM can be represented in percents of the average channel beat amplitude as

$$\mathrm{AM} = \frac{100}{kA} \sum_{j=1}^{k} |\mathbf{x}_j|,$$

where k is the number of samples in the selected beat interval. AM is useful for studying the signal amplitude distributions and their spatial changes. The average channel beat amplitude reflects the electrical power of the MECG signals (Fig. 5).

3.4. Isotemporal maps

The first objective of an isotemporal map TM is to display the spatial temporal distribution of an investigated activity in the heart muscle, as seen from the body surface. These activities are, for example, the peak of R-, P- or T-waves, the start or the end of these waves, or the time of J-point, etc. The activation moment should be determined in a reliable way, particularly if the signal-to-noise ratio is low and/or the time of the activation moment is not clearly defined, as by the peak of the T-wave. Currently, the most promising methods are based on the similarity between a selected interval, called a template, and the actual interval from the measurement. The template is defined as a set of consecutively sampled values s_l $l = j_\mathrm{b}, \ldots, j_\mathrm{e}$, where j_b and j_e are the indices of the first and the last template samples. Then the error, err, is calculated between the template and each sample set of $(j_\mathrm{e} - j_\mathrm{b})$ consecutive samples from the measurement as

$$err = (s_l - x_m)^2, \quad m = j, \ldots, j + (j_\mathrm{e} - j_\mathrm{b}).$$

The minimal value for err is found for each beat, indicating the time of maximal agreement between the template and the measured signal. The accuracy can be further improved by a quadratic polynomial interpolation, applied to the sample corresponding to the minimal err and its two neighbouring samples. Such an interpolation gives the time of the moment of interest with an accuracy one order of magnitude greater than the sampling time.

Alternatively, isotemporal maps can show time intervals between the activation moments on separate channels, or the variability of some intervals as QT or PQ on different channels. After the moments of the Q- and T-waves have been found, a QT-variability map can be generated, by showing the difference between T- and Q-time for a selected beat. In this way, a QT isotemporal map would show the possible spatial variability of the heart muscle depolarisation.

Isotemporal maps can be calculated for each particular beat, as an average of several beats, or as a sequence of an animated series of maps that reproduce the dynamic response of the heart repolarisation. However, one has to be cautious in interpreting the TM maps, because the computer algorithm for the activity detection can generate different artefacts if the signal-to-noise ratio is less than a certain value.

The activation map in Fig. 6 shows the time intervals between the first detected activity of the heart ventricles and the start of signal activity on all other channels. A computer algorithm, as described above, finds the first activity on all channels—the onset of the earliest Q wave. The channel with the earliest activation time is then found (in Fig. 6 left, electrode (5,3)) and is taken as the reference starting time. Then the differences from all other channels are calculated and shown in a TM BSM.

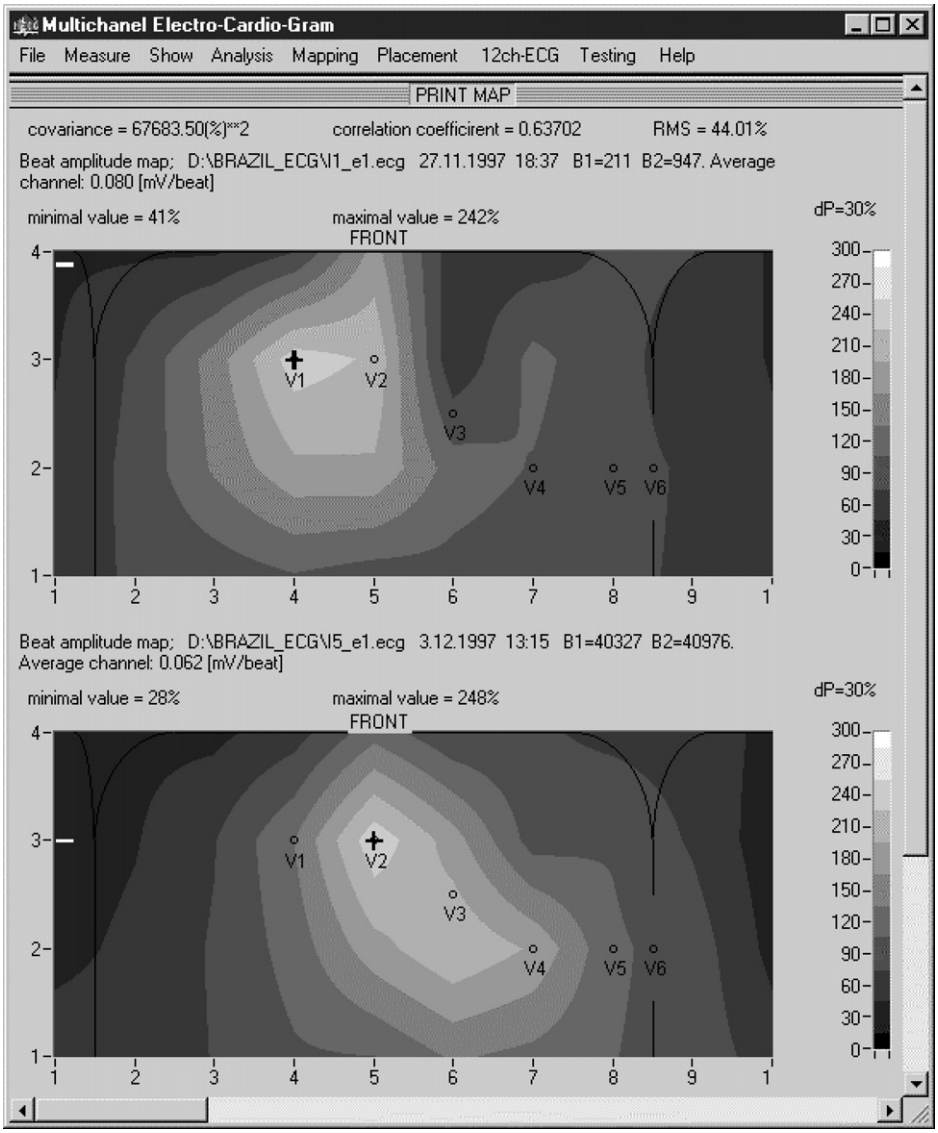


Fig. 5. Normalised beat amplitude BSM, taken from a preoperative measurement (above) and 5 days after surgery (below) show the amplitude distribution of MECG signals relative to the average channel amplitude. Before operation the average channel amplitude was 0.080 mV/beat with the maximal signal near V1 on position (4,3). Five days after the operation the average channel amplitude was 0.062 mV/beat with the maximal signal near V2 on position (5,3).

4. Conclusions

The limitations previously posed on BSM, such as great complexity or practical complications, cannot be justified today, because the procedures of body surface mapping are more reliable and provide a more accurate method for non-invasive analysis of the human heart. With the advent

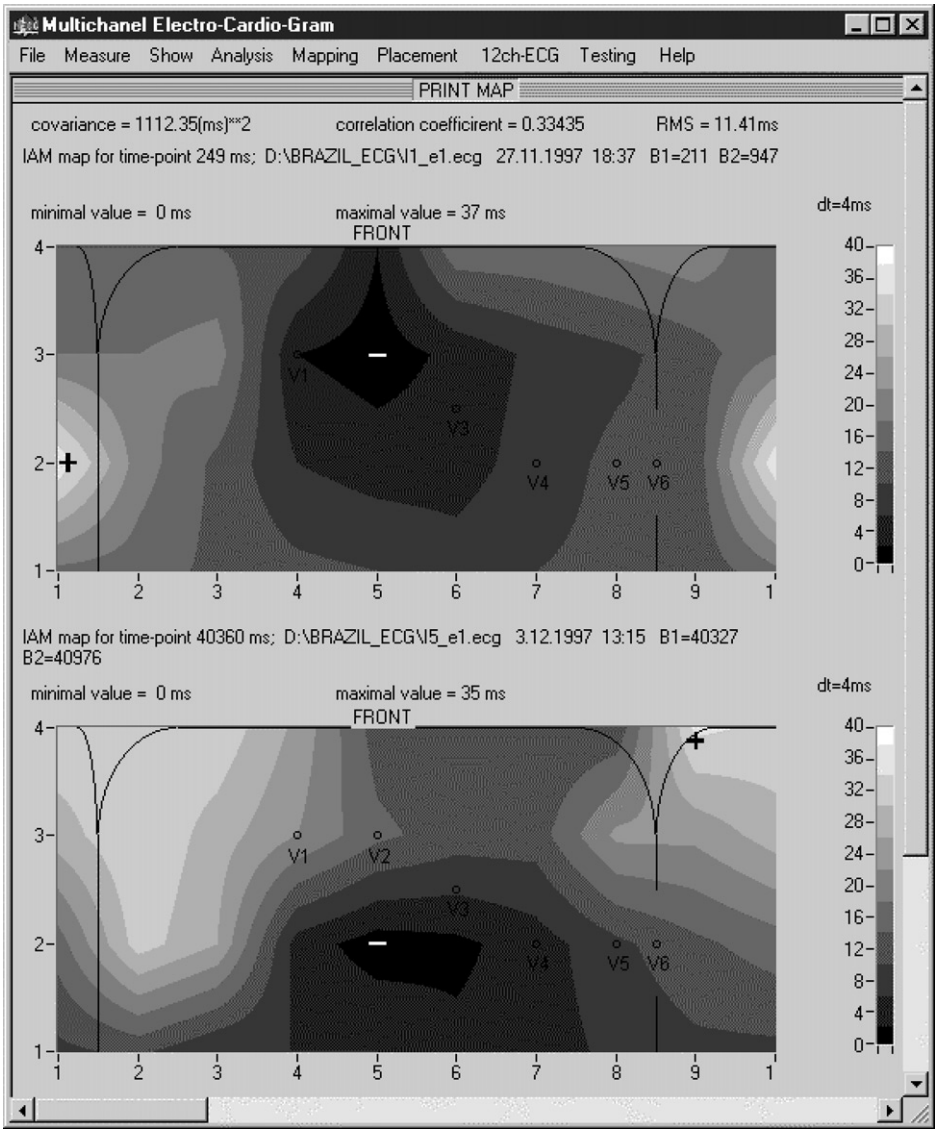


Fig. 6. Activation isotemporal maps, taken from a preoperative measurement (above) and 5 days after surgery (below). The baseline correction is performed first, the template interval is selected and the resulting time intervals found by computer algorithm. The data obtained are given on the TM with a maximal delay of 37 ms. A misinterpretation on the electrode (1,2)-left could be expected because of low signal-to-noise ratio. The place of the first detected activity of the heart has moved after surgery to (5,2).

of computers, powerful automatic algorithms can be implemented on-line, offering medical doctors more reliable and more specific heart disease diagnoses. The BSM system as described here is readily applicable for analysing electrical heart activity, together with the differences in the cardiac impulse propagation and their time variability.

The standard 12-lead ECG, even though not optimal, is still the only universally accepted practical method. We expect that in the future, different on-line health care systems [16] will need a minimised set of electrodes with potentially personalised positions and approximation coefficients that will reproduce the standard 12-lead ECG. MECG measurements are a useful tool in searching for a minimal set of electrodes, selected from the set of complete electrodes that can reproduce, for example, a standard 12-lead ECG.

5. Summary

Multichannel electrocardiography (MECG), an extension of the conventional electrocardiography aimed at refining the non-invasive characterisation of cardiac activity, has been used in body surface mapping (BSM). Increased spatial sampling on the body surface provides more in-depth information about the cardiac generated potentials. Graphical presentation of the surface potential can be a useful tool for personal or statistical analysis of different heart diseases. Much information can be read from appropriately drawn body surface isopotential maps that show the distribution of the potential at a selected moment, and isointegral maps that provide a distribution of the sum of potentials over a specified time interval (QRS, ST40, etc.). Other families of maps, such as normalised amplitude maps based on the characteristics derived from the complete analysed beat, are also described. Some new computer supported methods able to calculate automatically, for example, the QT-variability or temporal maps, are proposed. MECG measurements can be seen in this context as a powerful research and clinical tool for improved resolution of the measured results. The available redundant data can be used for validating a given diagnosis, for example in selecting the best channel for the QT-variability, or in searching for a minimal set of electrodes that can reproduce a standard 12-lead ECG.

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Roman Trobec received his B.S., M.S. and Ph.D. in Electrical Engineering from the University of Ljubljana. Since 1979 he has been with the Jožef Stefan Institute. Currently he is a principal investigator in the Department of Communications and Computer Networks. His group is involved in the design and development of parallel computing, computer simulations, medical data processing and digital transmission systems.