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PROCARDIO 8 – THE 8TH GENERATION OF THE HIGH RESOLUTION ECG MAPPING SYSTEM

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Abstract – In this paper a real-time data acquisition, visualization and signal processing software and an inverse-problem-solving method enabling non-invasive location of bioelectric sources in the heart are presented. Complete solution also consists of a portable measuring unit connected to a personal computer on which the software is running.

Acquisition and real-time processing and visualization software LiveMap is a client-server software for MS Windows. This modular open source software package provides real-time 2D and 3D visualization of various types of data mapped directly to a human chest model. It can compute isopotential and isointegral surface maps, as well as difference and departure maps applicable for direct heart or brain diagnostics.

For identification of local ischemia of myocardial cells an inverse method implemented in Matlab was included into offline ECG processing. It uses alterations in time integrals of surface potentials connected with changed repolarization of ischemic myocardial cells together with information on torso volume conductor to find an equivalent dipole representing the ischemic lesion.

Although the software can be used with variety of acquisition units, all its advantages can be achieved using a mobile measuring system which was developed in parallel to the software. It enables simultaneous recording of biopotentials measured in up to 128 body surface nodes relatively to a chosen reference potential. Active electrodes and intelligent data acquisition unit powered by a Li-ion cell enable to achieve high quality of measured signals. Connection to the USB port of a host computer over an optical cable minimizes capacitive coupling and guaranties high level of patient safety.

Keywords: Body surface potential mapping, real-time visualization, equivalent dipole model

1. INTRODUCTION

Body surface potential (BSP) mapping is a non-invasive electrocardiographic method for detailed registration of surface cardiac potentials using high number of sensing electrodes. It was shown elsewhere [1] that use of high quality BSP maps can help in more precise clinical diagnostics of cardiac diseases. However, several studies proved that BSP maps together with information on torso volume conductor obtained from MR, CT or ultra-sound imaging systems can be used for more advanced diagnostic methods based on inverse solutions and enable non-invasive model based assessment of abnormal electrical sources in the cardiac tissue [2, 3].

In this paper a real-time software for ECG acquisition, visualization and processing together with a high resolution ECG mapping system for BSP based cardiac diagnostics is introduced and possibility to use the system for non-invasive identification of local ischemic heart region is demonstrated.

2. METHODS AND MATERIAL

The software solution consists of two main parts: an online acquisition and recording software LiveMap and an offline processing application ProCardio which can be used for example for identification of local ischemia.

2.1. Real-time acquisition software

Acquisition, real-time processing, visualization and recording of multiple ECG signals are carried out by LiveMap package. LiveMap was especially designed for online pre-processing and visualization which can be carried out even during the measurement. The software can run on ProCardio measuring system in configuration with 32, 64 or 128 channels using sampling frequency ranging from 250 Hz to 2 kHz. Such configuration produces huge amount of data which must be processed without significant delay and therefore requires special programming techniques.

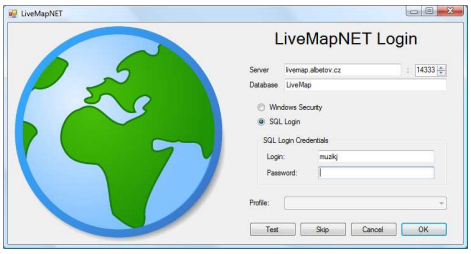

Fig. 1. Database login dialog

LiveMap is modular multitier client-server software. It uses SQL 2008 database engine for local or remote data storage. The database is used mainly for metadata, configuration and patient data storage. Measured data are preferably stored in standalone data files. This avoids rapid grow of the database - although when needed, data streams

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can be easily rerouted to the database using a SQL 2008 unique new feature – the Filestream. Using the database as a data-storage brings well known advantages of the multiuser concurrent access, assured data consistency and great development flexibility. Data access layer is implemented using LINQ to SQL.

Initially LiveMap was implemented in Delphi but later it was completely rewritten into .NET environment. From the beginning it was developed as fully modular system. Initially all modules were implemented as COM servers which were later used by the main application. Due to the compatibility between ActiveX and .NET there was no need to redefine the interfaces and all modules were rather continuously rewritten into .NET. When all the modules were reimplemented than also the main application was rewritten.

The application is implemented as a data processing pipeline so that the acquired data are being passed through the application and finally they are visualized and written to a data file. The modular pipeline structure is shown in Fig. 2.

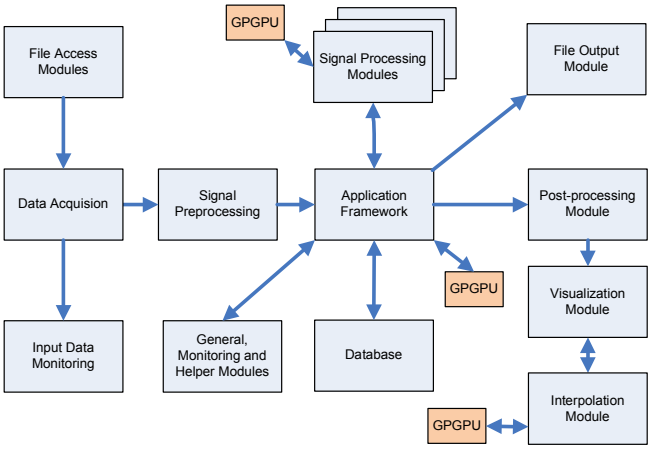

Fig. 2. Main modules of LiveMap software

The data processing pipeline consists of:

- signal acquisition module
- signal processing modules
- recording module
- visualization module

2.1.1 Data Acquisition

The first block of whole signal processing pipeline is the module for signal acquisition, so called VectorBroker. In fact, it is a special device driver with unified interface for communication and device configuration. So far several VectorBroker modules were developed and they all are mutually interchangeable. Some VectorBrokers can require further drivers to be installed in the system – i.e. NI-DAQ module which can acquire signals using National Instruments measurement modules. Currently implemented modules are for example: ProCardio, BrainScope, NIDAQ, BioSemi, File simulator and more.

Due to requirements on perfect patient isolation ProCardio measuring unit is connected to the PC USB port over an optical cable and the 245R FTDI chip is used as an USB interface. FTDI provides a set of communication libraries (even .NET wrappers) which could be used to build a communication module. On the other hand, it is also possible to communicate with the FTDI chip via a virtual serial port. Using the virtual serial port was finally easier, since it did not require any additional library.

2.1.2 Signal processing

Although recorded data are written to the data files in raw format (without any processing, as they were recorded), for the real-time visualization they have to be pre-processed. Signal processing consists of three steps.

In the pre-processing stage all signals have the baseline removed and optionally they can be filtered by FIR/IIR band-stop notch filter at 50/60 Hz for power line noise removal.

Main filter module is responsible for ECG segmentation. The segmentation is carried out only on one selected channel. It uses Hamilton QRS detector to detect R waves in the ECG and then the rest of waves is detected in between two QRS complexes. This all is done in real-time with delay of about 100-200 ms.

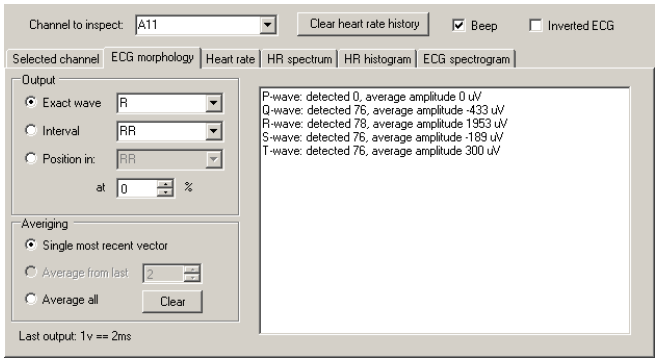

Fig. 3. ECG module settings

ECG processing module has a wide variety of parameters to be set. All the detection parameters can be modified during the measurement in real-time. Output of the module can be a vector of values from all channels, at percentage time between two waves (e.g. 30% between S and T peeks) or it can be used to calculate integral maps (e.g. QRS integral map). Output of the module is updated every time when a new hearth cycle is detected so the output delay is at maximum around 1s. In case of QRS integral map, the delay is only around 200ms.

2.1.3 Post-processing

Interesting information during the measurement is not only the actual BSP map but also the possibility to observe changes in BSP maps. This can be carried out using post processing module which is responsible for basic arithmetical operations on the maps. The operation is performed between the actual vector (the last output of the signal processing module) and a static vector. The static vector can be inserted into the post processing module from any external file or it can be captured during the measurement.

The combination of real-time segmentation, integration and map subtraction can be used also for a real-time calculation of difference maps.

2.1.4 Parallel processing and GPGPU

Since the real-time processing and visualization is highly computationally demanding, the software was designed to take the advantage of multicore/multiprocessor computers for parallel processing whenever it is possible. It can also use modern graphical adapters for massively parallel signal processing using GPGPU (General Processing on Graphics Processors Unit) techniques. Parallel processing is very useful especially for BSP maps processing since in many scenarios each channel can be processed independently on the others and in optimal case each channel is processed by dedicated shader processor. GPGPU can also be used for final calculation of interpolated maps when using Sheppard interpolation. In ideal state, each pixel of the final map can be calculated by single shader processor, since its value is independent on other pixels. In fact the maximum of shader processors on current hi-end graphics adapters is around 500 and calculated interpolated maps are usually 1000x1000 pixels so each shader calculates around 2000 pixels.

Fig. 4. - CPU vs. GPU architecture

Currently the GPGPU support is implemented for band-pass FIR filter, real-time spectrogram calculation and Sheppard interpolation of resulting maps. The advantage of GPU is more distinct the more channels/data are being processed. This is due to the significant overhead when moving data from main memory to graphics memory via PCI Express bus, which is significantly slower than FSB. An example of GPGPU calculation speed-up is shown Table 1. It presents calculation times for weight matrix (1000x1000 px, 64 channels) and one map interpolation.

Table 1. CPU vs. GPGPU calculation performance

	CPU	GPU - XNA	GPU - CUDA
Weight Matrix	16503ms	1365ms	173ms
Map Interpol.	2444ms	39ms	82ms

Hardware configuration was Intel Core 2 Duo 1.83GHz and nVidia Geforce 8600GTS. The table also shows the difference between two GPGPU platforms. In case of XNA the Sheppard interpolation algorithm was implemented in HSLS language and in the second case CUDA language was used.

2.1.5 Visualization module

The visualization module is responsible for presentation of calculated maps to the user. It can work in two modes: 2D – unfolded flat maps are drawn and 3D – the calculated and interpolated map is projected on a 3D model of the human chest, cylinder or any other model which is loaded from external files. For example, such a model can be constructed from a preceding tomographical examination.

Interpolation is carried out in 2D - resulting interpolated maps are transformed into textures which are directly drawn or they can be projected on a 3D chest model. Models can be transformed using affine transformation which is defined by a user modifiable 4x4 matrix. This allows universal models to be adjusted to the positions of electrodes. System works with models defined in XNA format (.xnb), freeware tools are available for conversion to this format.

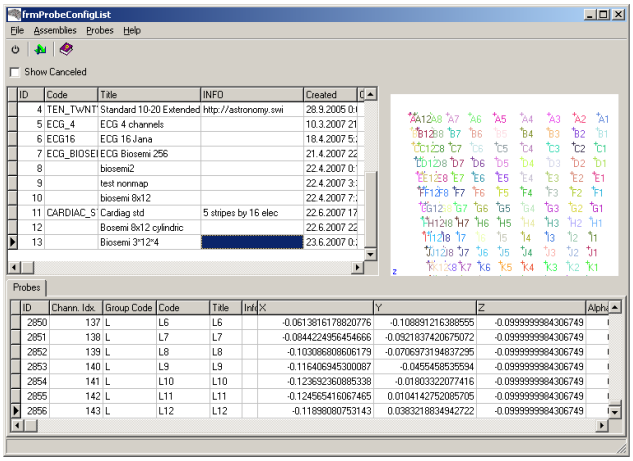

Fig. 5. Montage administration

The mapping itself consists of 3 steps. In the first step 3D positions of electrodes are recalculated to 2D using spherical or preferably cylindrical coordinates. In selected range, values measured or calculated for each electrode are interpolated into the whole texture using 2D Sheppard interpolation.

Advantage of this interpolation is that it uses precalculated matrix of weights. This matrix of weights is calculated only once before the acquisition and needs to be recalculated only when position of any electrode changes. This is however not expected during examination. Interpolated values are then represented in pre-generated color scale. When the interpolation is completed, generated texture is applied on simple plane – in case of 2D visualization or is applied on selected 3D model. Same method, which was used for flattening of 3D electrode mesh, is then used for backward projection of the texture onto the 3D torso model. Finally, the whole scene is rendered by the XNA (DirectX) subsystem

Initially the visualization module was implemented using managed DirectX (MDX) wrapper. Since MDX is not supported and developed any more the module had to be rewritten into XNA.

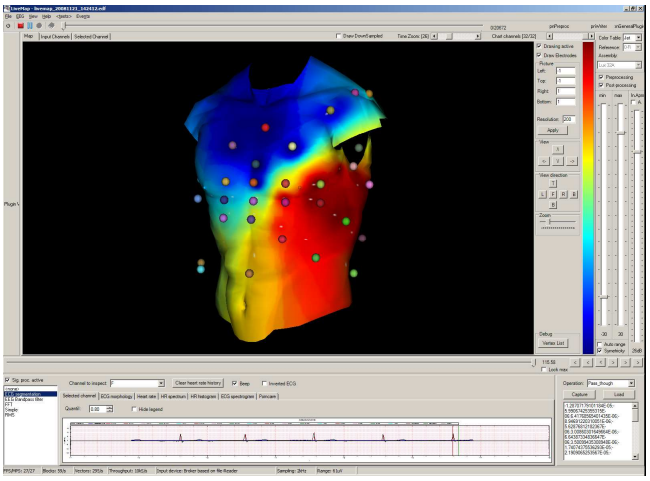

Fig. 6. Example of the application desktop during real-time BSP mapping.

2.1.6 Writer – Data Recording Module

Writer module, when present in the pipeline, provides storing of recorded data. Currently supported file formats are EDF+, GDF, BDF (BioSemi preferred format), D-files (BrainScope preferred format), .csv files and many others.

2.2. Software for offline mapping

ProCardio 8 application software is running under Windows/XP/Vista and was developed in Matlab environment.

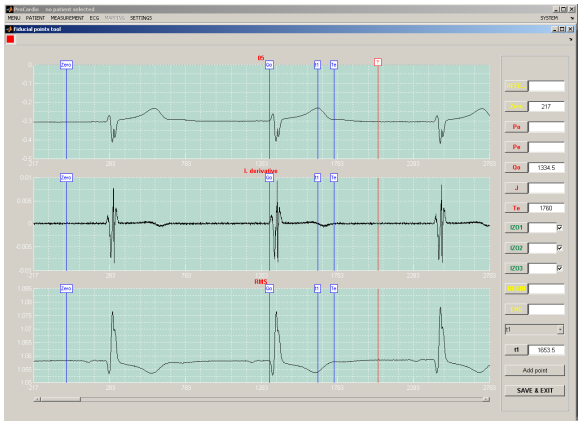

Fig. 7. Precise manual/semi-automatic signal measurement

It contains an alternative measuring program which can be used when no advanced real time data processing is desired. It controls the data acquisition unit, checks electrode contacts, reads data stream with ECG and control data, displays ECG signals on computer screen and stores them on disk as a GDF (general data format for biosignals) file. The other possibility is to work with GDF data files, which were previously recorded by LiveMap software.

Data processing and evaluation programs include interactive preprocessing of ECG signals (baseline correction, filtering, signal averaging, marking of desired events in signals, etc.) and mapping of body surface potentials or their time integrals. Difference or departure maps can also be evaluated. Presentation of 2D maps or 3D maps projected on the torso surface is possible.

2.3. Mobile measuring unit

ProCardio 8 BSP mapping device (Fig. 7) was developed to acquire high quality multi-channel ECG recordings and to compute BSP maps suitable for immediate clinical diagnostics and for advanced model-based interpretation of mapped data. The device consists of a data acquisition unit and a notebook computer controlling the data acquisition, processing of measured ECG signals and their analysis and electro-physiological interpretation.

ECG signals are sensed by active electrodes formed by disposable passive electrodes attached to active adapters made in SMD technology (Fig. 8). While use of quality disposable Ag-AgCl electrodes guarantees low noise, minimal polarization potentials and eliminates risk of patient infections, high input and very low output impedance of the active adapter effectively reduces disturbing signals often induced in electrode cables.

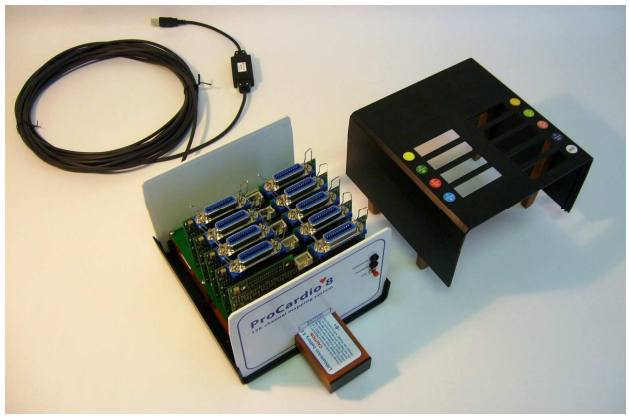

Fig. 8. Opened patient terminal box with one reference and four 16-channel boards, optical interface cable and Li-ion battery module

Modular data acquisition unit placed in the patient terminal box consists of several measuring boards plugged into a motherboard containing the microcontroller, USB interface and switched power supply module. Each measuring board has up to 16 analog input channels; all signals are measured relatively to a common mode sense (CMS) electrode that can be attached to the patient's body so that the interference from the common mode is minimal. One of the measuring boards is configured as the reference board and contains circuitry for the CMS electrode and driven right leg (DRL) electrode that further reduces the common mode voltage. It also limits current through the patient body to 50 µA and protects the patient in case of electrical defects in the unit. Additional protection circuit generates a power-down signal if the current remains close to 50 µA. This board is also used for recording of limb leads signals R, L, F. Signal of the Wilson's central terminal (WCT) that is commonly used as the reference for unipolar

ECG leads is generated as well. Remaining 12 channels on the board can be used for additional unipolar leads.

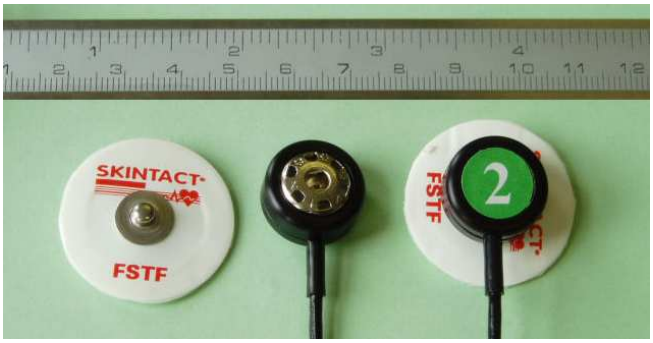

Fig. 9. Active electrodes are composed of quality Ag-AgCl disposable electrodes and active electrode adapter

Each low noise (< 1.0 μV_{RMS}) measuring channel is equipped with a DC-coupled instrumentation amplifier (gain 40) and a 22-bit Σ-Δ A/D converter. Sampling frequency can be set between 125 and 2000 Hz, resulting in effective dynamic resolution between 19 and 16 bits.

The data acquisition system is controlled by 16-bit CISC Fujitsu microcontroller. Its 4 UARTs and DMA controller are used to control the multi-channel measuring unit and to communicate with the host computer. Serial data sampled from analog channels are streamed over an USB FIFO circuit that provides bidirectional data transfer with rates of up to 1 MB/s. To minimize capacitive coupling between the patient terminal and the USB port of the host computer, a fibre optic USB extension cable is inserted.

The patient terminal is powered by a Li-ion cell. Advanced power management allows its use for one working day without replacement or recharging.

2.4. Non-invasive identification of ischemic lesions

Differences between surface potentials recorded under normal conditions and during ischemia can be displayed as difference integral (DI) maps. DI maps corresponding to QRST interval in ECG signals were used for non-invasive inverse assessment of the heart region with ischemia.

Supposing a small ischemic region, differences in BSP can be interpreted as being caused by single dipolar generator located at the centre of the region. To guarantee localization of the dipole within the heart walls we used a fixed dipole model located at one of predefined locations in the myocardium. For each of these locations i=1,2,…n, an equivalent dipole (ED) source representing changes in body surface potentials was estimated using the formula:

$$\boldsymbol{D}_i = \boldsymbol{T}_i^{+}\boldsymbol{\Phi} \qquad (1)$$

where D_i is an estimate of the dipole moment of an ED located at the i-th predefined position that in fact represents integral of the dipole moment of physical current dipole during the QRST interval (depolarization-repolarization period), T_i^+ is a pseudoinverse of the transfer matrix representing relation between position of the dipole and surface potentials and reflects geometrical and electrical properties of the torso volume conductor, Φ are differences in QRST integrals of surface potentials in mapped surface points. To solve the inverse problem of finding D_i, pseudo-inverse T_i^+ was computed for each dipole location i using singular value decomposition of T_i. To select the ED that best represents changes in surface potentials, criterion of minimal rms difference between the measured DI map and map calculated in the same surface points using the ED as an equivalent source was used.

2.5. Experimental data

Averaged ECG data from 4 persons without history of cardiac disease and 7 patients suffering from effort angina pectoris were recorded using the Amsterdam lead system with 62 surface electrodes. One ECG record of 1 minute length was taken before and five records every 3 minutes after sublingual nitroglycerine application. DI maps were computed as differences between QRST integral maps from all records after the nitroglycerine application and the first record. Maps were corrected for changed heart rate (HR) between the measurements using direct QT measurement or its estimation from corresponding R-R interval. Common realistic inhomogeneous torso and heart model geometry were used to find an ED representing changes in the BSP. Possible positions of ED were defined at gravity centers of 28 anatomical segments of a realistic heart model.

3. RESULTS

In all persons, except one person without disease history that was excluded from further evaluation, nitroglycerine administration was followed by increase of heart rate with a peak effect predominantly 3-6 minutes after application. Relevancy of DI maps for inverse identification of possible local ischemia was examined by evaluation of relative rms differences between QRST integral maps from records before and after the nitroglycerine application. To account for possible intra-individual variability in averaged QRST integral maps, only rms differences greater than 15% were considered significant. One “healthy” subject (h4) and three patients without medication (p1, p2, p4) fulfilled this criterion and their DI maps were inversely approximated by single ED.

Relative rms error between measured DI map and map produced by the ED was 33% for h4 subject and 51%, 60% and 31% for patients p1, p2 and p4, respectively. Sample results for patient p4 are shown in Fig. 9. As it can be seen, compensation of HR changes between the measurements influenced the position of the estimated ED. However, use of different compensation methods had little influence on the resulting ED.

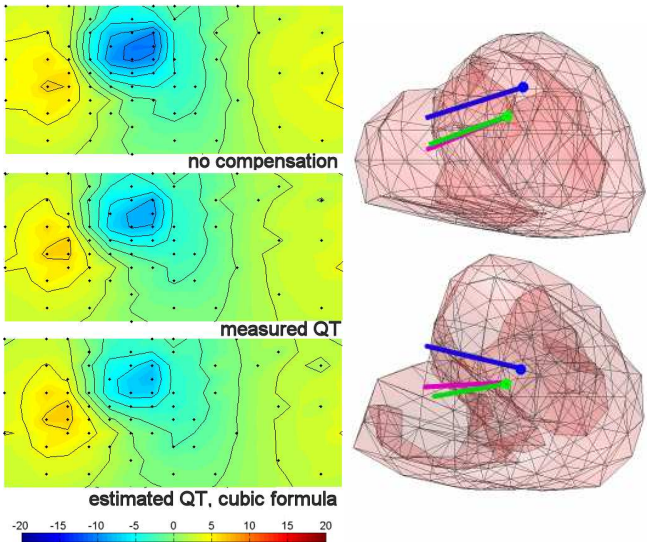

Fig. 10. *Left:* DI maps of the QRST interval in patient p4 (scale in mV. ms) computed without compensation of HR changes between the measurements (top) and with HR compensation using measured QT intervals (center) or using QT intervals estimated from changed R-R interval (bottom).
Right: Two projections of realistic ventricular model with corresponding inversely estimated EDs representing possible locations of the ischemic lesion (blue - no compensation, red - measured QT, green - estimated QT).

4. DISCUSSION AND CONCLUSIONS

Complex hardware and software solution for real-time signal visualization and cardiac mapping and for off-line maps evaluation and analysis has been presented. The system has been tested in study which was focused on possibility of non-invasive identification of ischemic lesions. Our previous attempts to detect local ischemic regions by using departure integral maps [4] showed that changes in BSP are small when compared with normal inter-individual fluctuations and can hardly be detected by departures from mean normal maps. However, computer simulations [5] suggested that relative rms differences between normal and ischemic QRST integral maps can be 20-45%, correlations .45 to .99. These are greater than observed intra-individual variability in healthy subjects (5-20% rms, correlations >.98) what, in principle, allows their use for ischemia identification. Simulations also showed that use of the proposed method might be not appropriate for identification of large lesions where the single dipole model is not adequate and its location may not be in correspondence with the real lesion. Transmural lesions produce smaller differences in DI maps than it corresponds to their size and their identification is more difficult.

Simulated ED localization from 32 ECG leads provided slightly worse results than from 62 or 192 leads. Hence more than 32 leads should be used in future measurements. Use of a high resolution mapping system with sufficient number of measuring channels therefore seems to be crucial for practical implementation of the proposed method.

No individual torso geometry was available when the method was tested on real patients and common model geometry was used. Use of individual torso geometry should improve accuracy of the lesions localization [6].

Despite these limitations our results indicate that the developed ECG mapping device could be a useful tool for clinical implementation of ECG mapping methods, helping in non-invasive cardiac diagnostics using common BSP mapping methods. Moreover, it can help to identify small ischemic regions with changed repolarization using model-based interpretation of difference QRST integral maps.

ACKNOWLEDGMENTS

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