REVIEW

Three-Dimensional Electrogram in Spherical Coordinates: Application to Ischemia Analysis

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Summary

Three-dimensional electrogram was used for analysis of ischemia manifestation in isolated hearts. Three parameters based on spherical coordination system were used in this study – amplitude of electrical heart vector, its azimuth and elevation. The parameters were presented as a trend. This approach reflected ischemic changes in a manner which can be easily observed and evaluated. Ischemia was analysed in seven isolated hearts of New Zealand white rabbits. It was found that (a) ischemia changes heart electric vector, (b) ischemic preconditioning has a protective effect, and (c) both of these findings can be clearly observed by the proposed method.

Key words

Three dimensional electrogram • Vectorcardiogram • Spatiocardiogram • Vectorcardiography parameters • Myocardial ischemia

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Introduction

Rhythm of the heart is controlled by the sinoatrial node. Its electrical activity propagates to other parts of the heart by the conduction system and by the myocardial working tissue in various directions and at diverse velocity. Hence, the electrical field of the heart is clearly inhomogeneous and changes its direction and intensity in time.

The course of electrical field can be recorded either from the surface of the heart (*electrography)* or from the body surface (*electrocardiography-ECG)*. According to the number of electrodes and their distribution in space three types of records exist – one-dimensional record (1D), two-dimensional (2D), and three-dimensional (3D) records (Fig. 1, part A). Body surface records are the following:

- 1D record (ECG) represents the time course of electrical activity recorded by either a simple active electrode – unipolar lead, or by two equivalent electrodes – bipolar lead.
- 2D record is achieved by two pairs of bipolar leads perpendicular to each other (*orthogonal leads*). The resulting loop is termed *vectorcardiogram* (*VCG)*.
- 3D record uses three perpendicular orthogonal leads. The loop obtained is called *spatiocardiogram (SCG)*.

ECG represents the time course of the electrical signal. Vectorcardiogram pictures successive instantaneous mean electric forces from the heart throughout the cardiac cycle (Acierno *et al.* 1994). Spatiocardiogram and vectorcardiogram are usually represented as a loop consisting of a sequence of coordinates.

Nomenclature of multi-dimensional electrograms is not defined yet, thus in this article one-dimensional electrogram was abbreviated to 1DEG, and similarly 2DEG and 3DEG represented two-dimensional, respective three-dimensional electrogram (Fig. 1, part B).

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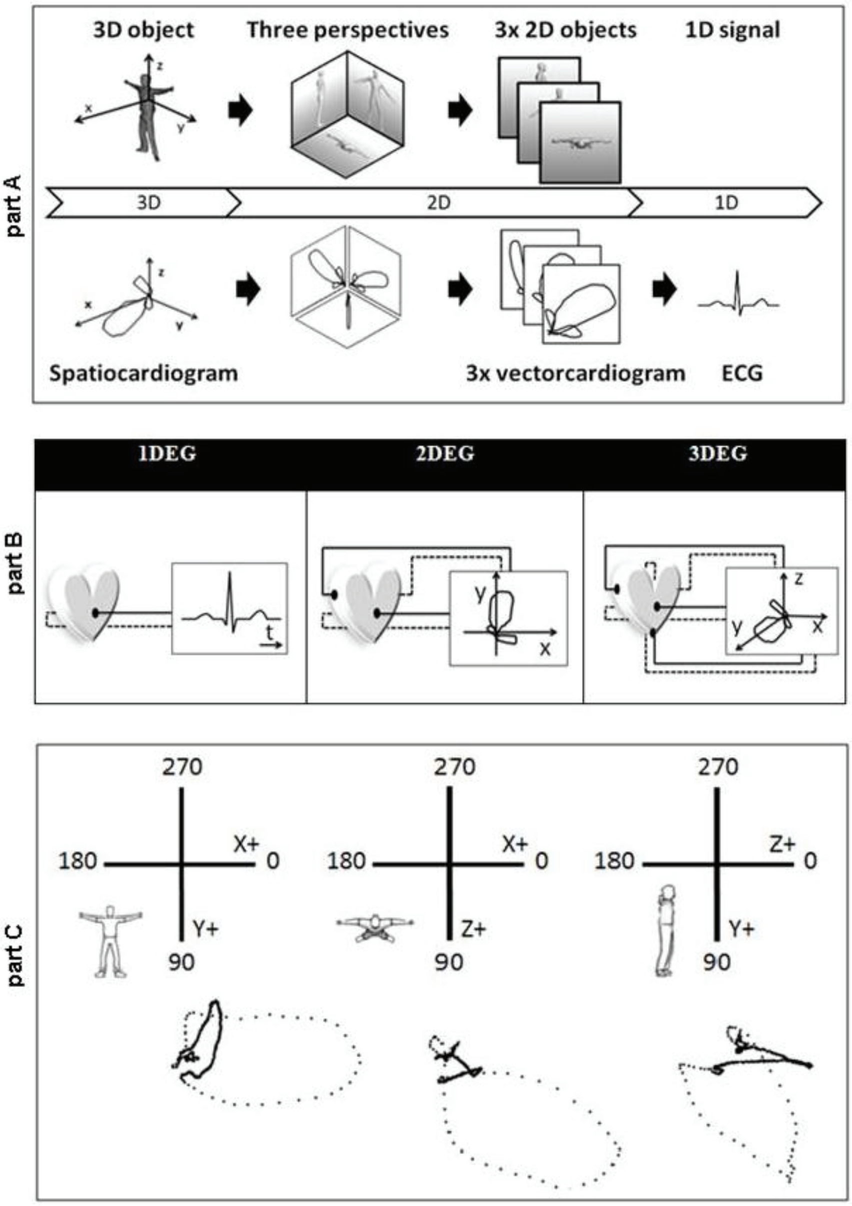

Fig. 1. Part A: Diagram of the transformation from spatiocardiogram through vectorcardiogram to electrocardiogram; **Part B:** Nomenclature of electrograms used in this article; **Part C:** Orthogonal projection based on axes X, Y, Z yield three two-dimensional loops (VCG). Dots indicate timing of ventricular depolarization (0.5 ms).

The one-dimensional electrocardiogram became the undeniable, universal and standard clinical tool. Utility of 2D vectorcardiogram is still a matter of debate. Both ECG and VCG reflect the same electrical phenomenon in the heart, but in a different scope. Some of modern electrocardiographs record and store VCG and 12-channel ECG is derived and displayed thereof. Good review about this topic has been published recently by Riera (2007). The reason why medical equipment producers choose this way of representation is complete establishment of electrocardiography in medical practice. Spatiocardiogram is the most complicated one of the three abovementioned tools. An ideal system for spatiocardiography would consist of three orthogonal vectors of equal length. Four electrodes are the minimum required theoretically in any system of spatiocardiography, since three independent potential differences are necessary to determine the heart vector in three dimensions (Frank 1956). SCG is difficult to analyse by visual perception only. An excellent basis for spatiocardiography constiduted V. Laufberger (1980, 1981). He used Frank´s lead system to derive three orthogonal signals from the standart 12 lead ECG system. These signals Laufberger digitalized and processed by a computer programme. His pioneer work was limited by technical possibilities at that time. Even so he was able to demonstrate the utility of SCG for the assessment of heart condition, including ischemia.

The electrical forces in heart are visualized by orthogonal projections of vectorcardiographic loops

(Fig. 1, part C). Vectorcardiograms in frontal, sagittal and horizontal plains are the basis for construction of spaciocardiograms.

There was no technique available for visualization and recording of SCG in three-dimensional space until expansion of computers into cardiology. It was very difficult to get a clear picture of the real three-dimensional form of the loop using these projections (Rautaharju 1988). Frank declared already in 1956 in his breaking work that vectorcardiography has not been fully exploited because projections of vector loops onto the anatomic body axes have been commonly used rather than studying the loops in their own frame of reference (Frank 1956). A current possibility would be to use three-dimensional loops and to compute the SCG parameters. This procedure reduces the number of parameters required. Almost all present SCG evaluations are done by computer processing; therefore using the three-dimensional loop is undeniably more advantageous. Many various approaches in presenting a SCG loop were introduced with the aim to portray SCG loop as easily as possible. For example newer software for SCG presentation allows rotation of SCG loop together with simplified human torso, for better perception of the position in space.

Generally VCG and SCG can be analyzed either by a human (who only compares loop shape with a template) and/or by calculation of parameters extracted from these loops. The parameters can be subdivided into normalized and absolute parameters. The former are derived by comparison with the first (reference) loop measured in a patient. All loops are normalized to coincide best with the first loop (Fayn *et al.* 1983). However, this approach does not take into account possible changes resulting from different position of the patient or of inaccurate placement of the electrodes. The latter group – absolute parameters – is independent on the first loop, which describes the current loop. Parameters from both groups can be presented either separately or as a function of time – trend.

Evaluation of VCG

Since an introduction of vectorcardiogram and spatiocardiogram, the scientist have tried to find a way how to characterize the loops. Numerous approaches and parameters have been reported (for overview see Table 1).

Although numerous parameters have been introduced during the last seven decades, none of the currently employed parameters seems to be explicit and easy to use, so there is still a strong need for parameter – or set of parameters – which can be exploited easily and also satisfactorily for description of vectorcardiogram or spatiocardiogram. Moreover ideal parameter should be robust against distortion factors, which may accompany the procedure of vectorcardiographic and spatiocardiographic records acquisition. Main distortion factors represent breathing movements and hemodynamic changes such as rotation and deformation of the heart, caused mainly by patient's movements. Aidu *et al.* (2003) reported that eigenvectors, eigenvalues, rotation angles and determinants can be used for correction of heart position, if deformation causes linear deformation.

Mathematical background of the method

Bardoňová presented a system of coordinates based on spherical coordinates (Bardoňová *et al.* 2008). Both in Cartesian and spherical coordinate systems, each point in the space can be described with only three numbers. They are:

- azimuth, elevation and length of vector for spherical coordinate system (Fig. 4, part A),
- distance from origin in coordinate ***x***, distance from origin in coordinate ***y***, and distance from origin in coordinate ***z*** for Cartesian coordinate system.

Both coordinate systems can be interchanged mutually. Equations 1-3 describe conversion from the Cartesian coordinate system to the spherical one; equations 4-6 describe conversion from spherical to Cartesian coordinate system.

$$\vartheta = \arctan(y / x) \qquad \text{Equation 1}$$

$$\varphi = \arctan(z / \sqrt{x^2 + y^2}) \qquad \text{Equation 2}$$

$$r = \sqrt{x^2 + y^2 + z^2} \qquad \text{Equation 3}$$

$$x = r \cdot \cos(\varphi) \cdot \cos(\vartheta) \qquad \text{Equation 4}$$

$$y = r \cdot \cos(\varphi) \cdot \sin(\vartheta) \qquad \text{Equation 5}$$

$$z = r \cdot \sin(\varphi) \qquad \text{Equation 6}$$

Table 1. Summary of parameters used for VCG or SCG description.

Parameter	Author	Purpose
Forces (initial, early and terminal) *Openness of loop*	Wolff (1955)	Establishing of heart's position and diagnostic of septal disease Infarction diagnosis
Maximum vector *Maximum width* *QRS angle* *Direction of rotation*	Howitt and Lawrie (1959)	Myocardial infarction localization
Planarity of QRS loop *Roundness of QRS loop*	Pipberger and Carter (1962); Horinaka *et al.* (1993)	Myocardial infarction diagnosis
Clockwise and counter clockwise rotation of initial forces *Initial forces and elevation and direction of early vectors*	McNeill *et al.* (1975)	Myocardial infarction analysis
Order of octant	Laufberger (1980)	Ischemia analysis
Maximum angle between QRS and T-loop axes *T-axis elevation and azimuth angle difference* *Ratio of maximum and mean T-vector magnitudes*	Bortolan and Christov (2001)	Myocardial infarction analysis
Length and angle of heart electric vector after transforming to new coordinate system based on singular value decomposition	Janusek *et al.* (2008)	T-wave alternans studies
Shape of combined vectorcardiograms plots	Ghista *et al.* (2009)	Diagnosis of ventricular pre-excitation and in the localization of the bypass tract
Maximum module of the depolarization vector *Volume* *Planar area* *Maximum distance between centroid and the loop* *Angle between XY plane and optimum plane* *Relation between the area and perimeter*	Correa and Laciar (2009)	Cardiac ischemia induced by percutaneous transluminal coronary angioplasty

Although there is no difference in the number of required parameters, the spherical coordinate system is superior to the Cartesian coordinate system concerning the usefulness for SCG description. There are two major statements on support of the above preposition:

1. Much more attention is paid to changes of SCG angles, than of the magnitude of vector.
2. Angles describe space more smoothly than ***xyz*** coordinates. Every crossing of zero at coordinates

makes a change in sign. There is three zero crossings at Cartesian coordinates for SCG: +/– ***x***, +/– ***y***, and +/– ***z***. However there are only two zero crossings at spherical coordinates, if the following ranges are used for SCG description: azimuth is the range of <0, 2π> radians, elevation is in the range of <0, 2π> radians and length of vector must naturally be positive. Therefore, spherical coordinates are more suitable for presenting the trends, in which every discontinuity leads to a disruption of visual perception.

Although many parameters derived from SCG loop are currently used, only few authors deals with the presentation of SCG parameters as a function of time. However, trends may be used in diagnoses of patients with advantage because the trends are easy for human's evaluation.

Boxplot

3DEG signals were measured in this study. For better transparency values of chosen parameter in range of one minute were grouped together. Each this group was presented in a form of boxplot. Basics of boxplot are presented in Fig. 2, part B.

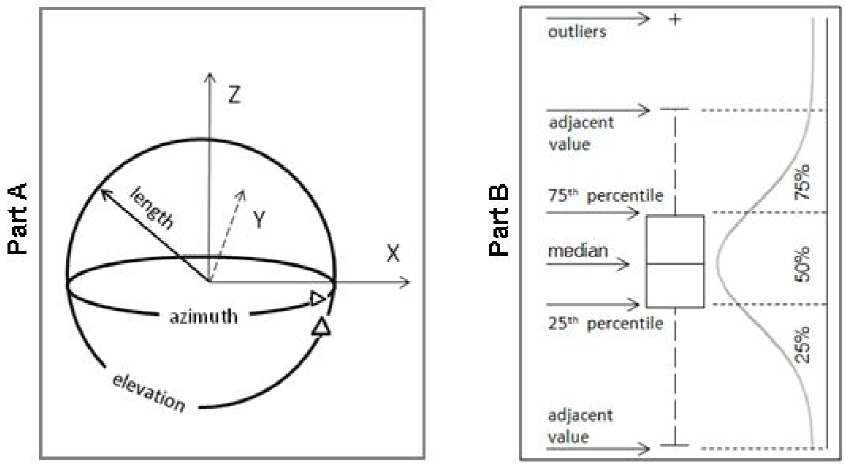

Fig. 2. Part A: Coordinate system used in this article. Azimuth and elevation have range 2π radians. Their orientation is described in text; **Part B:** Shape of curve of normal probability distribution is Gaussian curve. Curve is drawn in this picture on the left side. Range from 25th percentile to 75th percentile represent 50 % of all measured values. Adjacent values represent borders for 24.65 % (on picture show rounded as 25 % and 75 %) of values at each side of Gaussian curve. The width of box bordered by 25th and 75th percentile show how tightly values surround median.

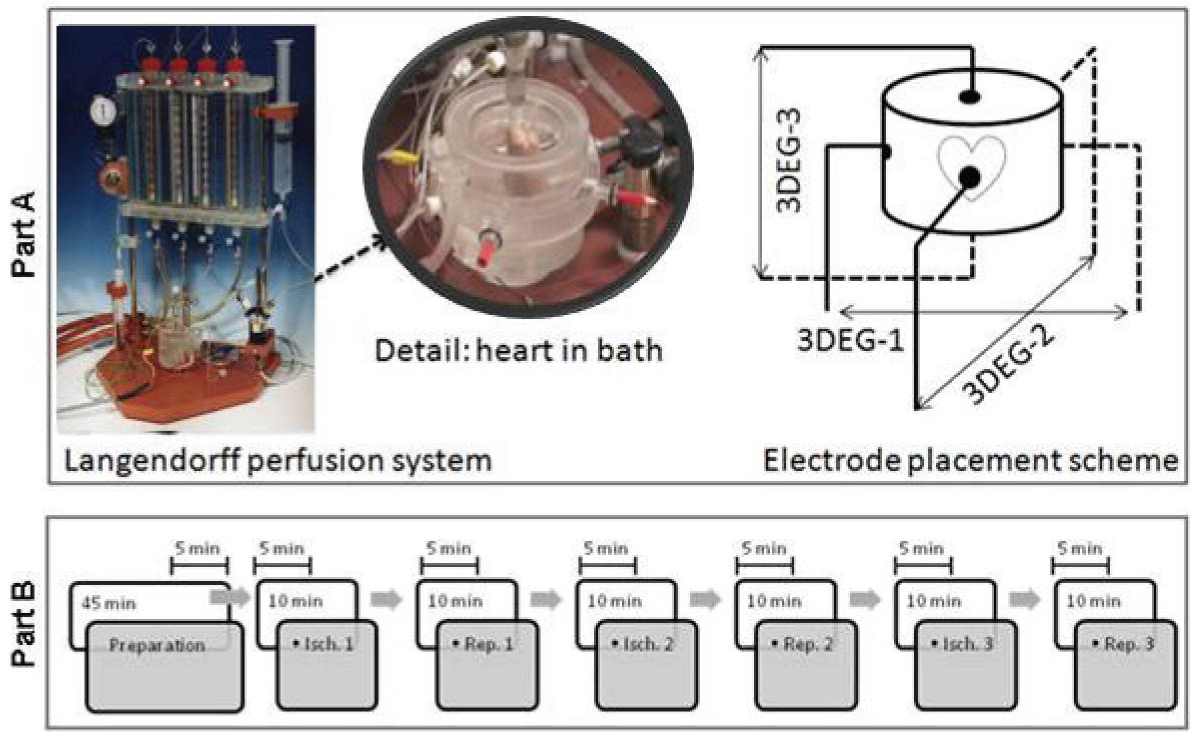

Fig. 3. Part A: Experimental setup. Isolated perfused heart is placed in a bath with build touchless electrodes (digram on the right); **Part B:** Chart flow of the experiment. Isch – period of ischemia, Rep – period of reperfusion.

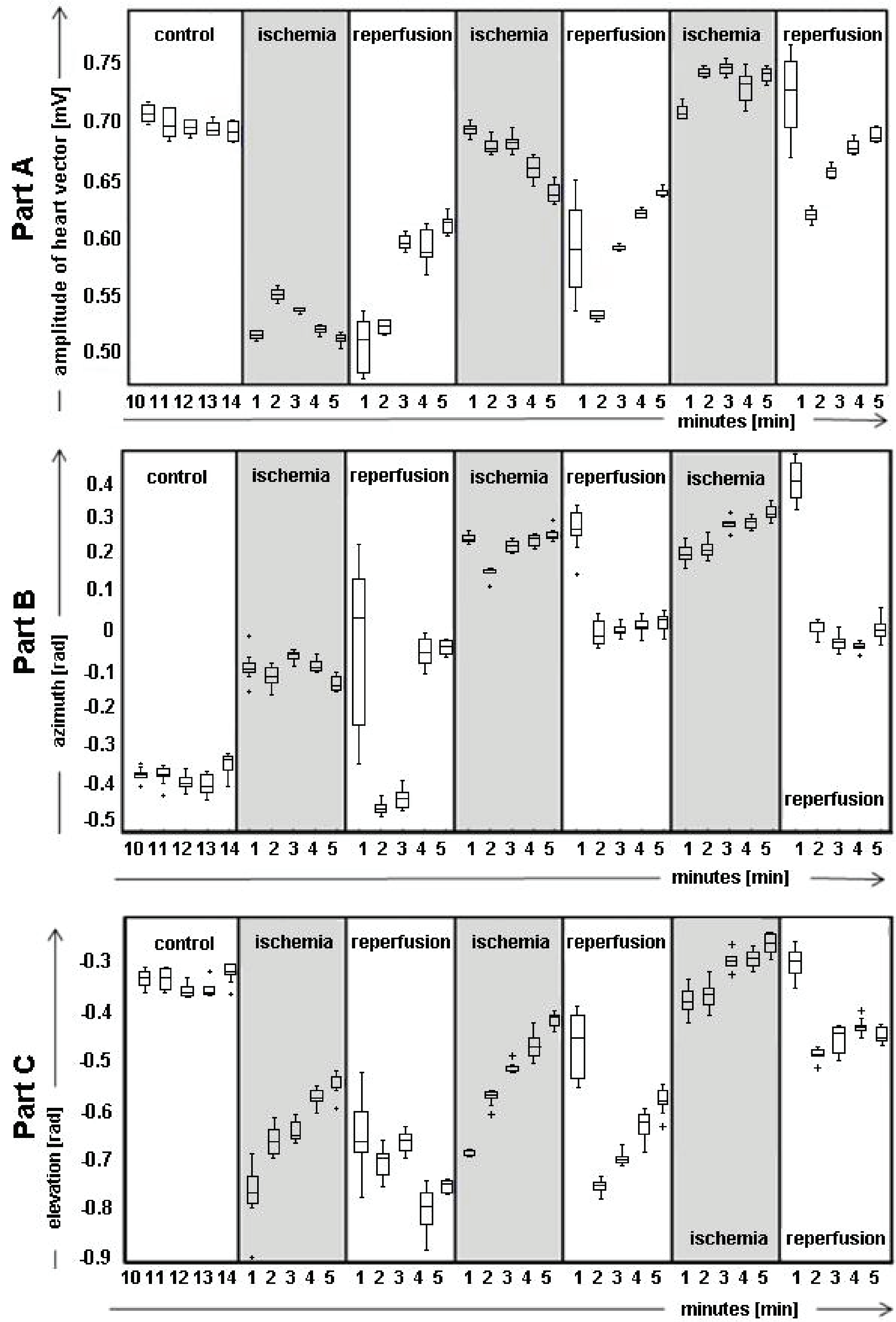

Fig. 4. Part A: Amplitude of heart vector in QRS segment. Phases of experiment are in according to scheme of experiment, which can be seen at Figure 3, part B; **Part B:** Amplitude of azimuth in QRS segment. Phases of experiment are in according to scheme of experiment, which can be seen at Figure 3, part B. A large dispersion in each first minute of reperfusion reflects rapid changes during the first 60 seconds of reperfusion; **Part C:** Amplitude of elevation in QRS segment. Phases of experiment are in according to scheme of experiment, which can be seen at Figure 3, part B. A large dispersion in each first minute of reperfusion reflects rapid changes during the first 60 seconds of reperfusion.

Experiments

The setup for recording of 3D electrogram in isolated aortic perfused heart was developed in our laboratory. The heart is placed in a bath with three pairs of touchless orthogonal electrodes (Fig. 3, part A).

All experiments followed the guidelines for animal treatment approved by local authorities and conformed to the EU law. Seven New Zealand rabbits were included in the study. In deep anaesthesia with xylasine and ketamin, the heart was excised and fixed on perfusion set-up filled with Krebs-Henseleit (K-H) solution (1.25 mM Ca^{2+}, 37 °C) and placed in a bath. The hearts were perfused according to Langendorff in the mode of constant perfusion pressure (85 mmHg). The hearts were stabilized for 30 minutes, and after stabilization three repeats of ischemia + reperfusion (10 minutes each) periods followed. In this study, six Ag-AgCl disc electrodes in three orthogonal directions x, y, and z were placed in the walls of the bath which is part of the perfusion system. Each isolated rabbit heart used in this study was positioned in the same way in the bath. ECG signals were recorded by data acquisition multifunction card PCI-6250 (National Instruments, USA) with sampling frequency fs=2000 Hz and acquired by designed application in LabView 7.1 software (Texas Instrument, 2008). The 16-bit analogue to digital conversion was used. The digitalized signal was stored on a hard disk for further off-line processing.

The signals were split into 7 parts in Matlab R2006a (MathWorks, 2006). The first part was taken from the last 5 minutes from control period, other parts was taken from the first 5 minutes of relevant period. Scheme of experiment is shown at Figure 3, part B.

Amplitude of the heart vector in 3DEG was noticeably changed in ischemia and reperfusion (Fig. 4). Degree of change depended on number of ischemic periods (Fig. 4, part A). During the first ischemia, the amplitude significantly decreased, but returned to normal on the first reperfusion. The effect of the second and the third ischemic periods was less apparent. Elevation and azimuth (Fig. 4, parts B and C) have the same pattern for the second and third periods of ischemia.

The use of three-dimensional SCG together with a coordinate system based on two angles may be helpful for visualization of SCG in a form of trend. This approach was used in our analysis of the effects of ischemia. Noticeable changes may be seen in ischemia and reperfusion as far as the length of vector, azimuth and elevation in Q-S segment is concerned. Limitation of this method by distortion factors like breathing movements, changes in position and deformation of the heart degrading the trends are minimized in the isolated perfused heart.

It can be concluded that the change of the electrical vector of the heart as well as the protective effect of ischemic preconditioning may be observed by analysis of trends in 3DEG.

Conflict of Interest

There is no conflict of interest.

Acknowledgements

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