Electrocardiographic ST segment changes as an indicator for localization of injury potentials. A computer simulation study

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Some results of mathematical modeling of an electrocardiographic method for location of cardiac ischemic injury are presented. The method uses unipolar signals of classical Frank lead electrodes, which are sensitive to the spatial position of the electrogenic regions in the myocardium. The values of lead signals corresponding to the shifted ST segments of electrocardiograms are considered, and the generator midplane of the ischemic region is determined with the use of simplified electrodynamic relationships. This plane is oriented normally to the ischemic heart vector and approximately characterizes the spatial position of the lesion boundary on the myocardium surface (endocardium or epicardium). To estimate the accuracy of the method, a comprehensive computer model of the cardioelectric generator and body as conducting medium is used and several versions of acute ischemic lesions with different localizations at the ventricular walls and septum are considered. For lesions situated at the opposite free walls of the ventricles, the resulting position errors of the midplane in the direction of the injury vector do not exceed 0.7 cm: therefore it is possible to identify the injured ventricle of the heart with satisfactory accuracy.

Key words: Cardioelectric generator – Ischemic lesion – Electrocardiographic models

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V článku sa uvádzajú niektoré výsledky matematického modelovania elektrokardiografickej metódy na lokalizáciu ischemického poškodenia srdca. Metóda používa EKG signály, unipolárne merané z klasických Frankových zvodových elektród. Tieto signály sú citlivé na priestorovú polohu elektrogénnych oblastí v myokarde. Do úvahy sa berú potenciálové hodnoty posunutého ST segmentu elektrokardiografických signálov v jednotlivých zvodoch, z ktorých sa pomocou jednoduchých elektrodynamických vzťahov určí stredová rovina ischemickej oblasti. Táto rovina je kolmá na srdcový vektor poškodenia (ischémie) a približne charakterizuje priestorovú polohu ohraničenia lézie na povrchu myokardu (endokarde alebo epikarde). Na zistenie presnosti tejto metódy sa používa celkový model, ktorý pozostáva z modelu srdca ako kardioelektrického generátora a z modelu hrudníka, ktorý predstavuje nehomogénne vodivé prostredie. V modeli srdca sa simulovalo niekoľko verzií akútnych ischemických lézií, rozlične lokalizovaných v stenách komôr a v medzikomorovom septe. Pri léziách, ktoré sa lokalizovali vo voľných bočných stenách komôr výsledné chyby určenia polohy stredovej roviny v smere vektora poškodenia nepresahujú 0,7 cm, a preto táto metóda umožňuje určiť oblasť poškodenia v srdcových komorách s vyhovujúcou presnosťou.

Kľúčové slová: kardioelektrický generátor – ischemická lézia – elektrokardiografické modely

Introduction

One of the important problems of electrocardiographic diagnosis lies in determining of the degree and location of the ischemic injury. There are well known efficient methods for solving this problem by body-surface electrocardiographic mapping with the use of rather complicated measuring procedure requiring several tens of leads (1). Since the multiple lead systems of electrocardiographic mapping are not always applicable under conditions of practical diagnosis, we proposed in (2, 3) a simplified method for estimating the characteristics of the ischemic zone on the basis of unipolar measurements made by the electrodes of a vectorcardiographic Frank lead system with respect to the Wilson terminal. The combination of electrodes (termed as Frank-M system) includes the same number of electrodes as the standard 12-lead electrocardiographic system **(Figure 1)**.

Here, a modified version of the aforementioned method is described and some results of determining the required parameters and estimating the errors of the method are presented. The investigation was carried out on a sophisticated interactive computer model of the heart as electric generator and body as volume conductor (4, 5).

Electrophysiologic investigations imply that the electric generator set up by the local zone of acute is-

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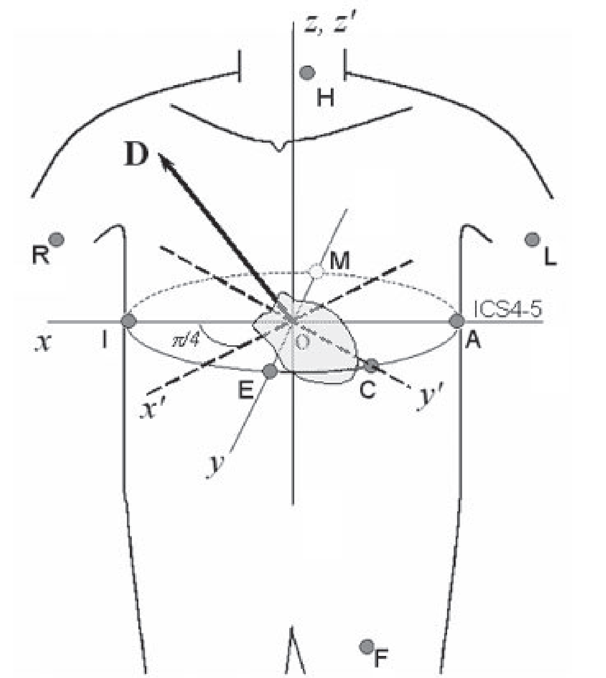

Figure 1 Electrode positions of the Frank-M lead system and axes of the coordinate systems used. The coordinate planes *xOy* and *x′Oy′* lie at the level of 4-5th intercostal space (ICS4-5)

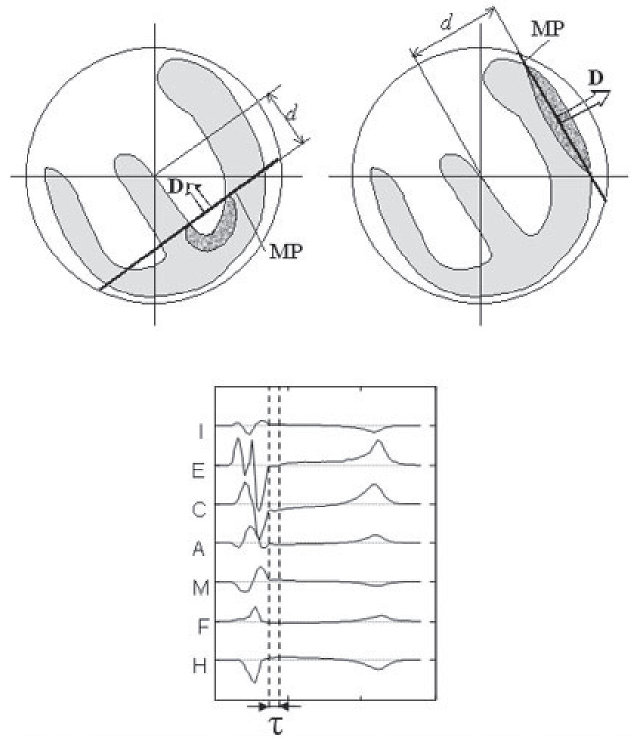

Figure 2 Above, subendocardial (left) and subepicardial (right) zones of injury in the heart cross-section, the midplane (MP) is indicated by the heavy straight line, D is the heart injury vector. Below, interval τ of shifted ST segments of unipolar electrocardiograms used for determination of the midplane.

chemia in the heart can be represented with sufficient practical accuracy as an equivalent uniform electric double layer coinciding with the boundary between the regions of ischemic and healthy myocardium (**Figure 2**). The dipole moment density at each point of this double layer (double layer moment) is proportional to the difference of the action potential amplitudes in the cells of the aforementioned regions and is directed from the healthy region to the ischemic region. The double layer moment is maximum in the complete injury of the ischemic cells, when the cells are not able to polarize. The magnitude of the ischemic heart vector (total dipole moment of the cardioelectric generator produced by the boundary between injured and normal tissues) is proportional to the aforementioned difference of the action potential amplitudes and the area of the double layer projection onto the plane perpendicular to the ischemic heart vector. This vector coincides closely with the normal to the heart wall surface near the midpoint of the ischemic zone. The plane situated with minimum deviation from the double layer boundary is referred to as the generator mid-plane. This plane is perpendicular to the ischemic heart vector and displaced with respect to the geometric heart center, thus it characterizes the general position of the ischemic zone in the heart ventricles. In the case of transmural ischemia, the midplane would lie between the endocardial and epicardial boundaries of the ischemic zone.

The acute ischemia results in a stable shift of the systolic segment ST of the electrocardiogram. So, for estimating the injured zone position, the generator midplane should be determined at the middle part of the ST period.

Method

The cardioelectric potentials are measured by the aforementioned Frank-M lead system. It includes electrodes of the classical Frank vectorcardiographic lead system, in particular, the electrodes I, E, C, A, M in the transversal plane passing through the heart center and electrodes H and F on the head and left leg, respectively, with the additional electrodes R and L on the right and left arms, respectively (**Figure 1**). The primary signals are the unipolar potentials of the measuring electrodes with respect to the Wilson terminal, while the signals proportional to the three components of the heart vector **D** (calculated by the Frank relations) are also used. This vector defines the direction of midplane shift sought for. Along with the main coordinate system *xyz* with the origin at the geometric center of the chest, the auxiliary system *x'y'z'* turned through the angle $\pi/4$ around the *z*-axis, is used. The latter coordinate system is more convenient for the problem considered, taking into account the asymmetric position of the heart in the chest.

A hypothetical point generator situated at the midpoint of the ischemic lesion is formulated. On the positive and negative *x'*, *y'*, and *z'*- semiaxes, imaginary measuring points are considered at distances $r_{x'}, r_{y'}, r_{z'}$ from the coordinate origin. The potential at a particular imaginary point is assumed to be a non-negative value equal to the averaged absolute values of the potentials at true measuring points situated in the same coordinate half-space. The true potentials are multiplied by correcting coefficients, approximately taking into account the main dimensions of the chest. In particular, potentials at the points E and M are multiplied by, ρ_b^2 and potentials at the points H, F, R, and L by ρ_h^2, where $\rho_b = \frac{b}{a}$, $\rho_h = \frac{h}{a}$; *a*, *b*, and *h* are transversal diameter, sagittal diameter, and height of the chest, respectively. Here, the mean values $\rho_b^2 = 0.5$ and $\rho_h^2 = 2$ are used. The potentials at imaginary measuring points on the positive and negative *x'*, *y'*, and *z'*-semiaxes are expressed, respectively, as

$$\varphi_{+x'} = \frac{1}{2}\left(|\varphi_I| + |\varphi_E|\right), \quad \varphi_{-x'} = \frac{1}{2}\left(|\varphi_A| + |\varphi_M|\right),$$
$$\varphi_{+y'} = \frac{1}{3}\left(|\varphi_E| + |\varphi_C| + |\varphi_A|\right), \quad \varphi_{-y'} = \frac{1}{2}\left(|\varphi_M| + |\varphi_I|\right),$$
$$\varphi_{+z'} = \frac{1}{3}\left(|\varphi_H| + |\varphi_R| + |\varphi_L|\right), \quad \varphi_{-z'} = |\varphi_F| \qquad 1.$$

where subscripts I, E, C, A, M, H, F, R, L indicate the true measuring points.

By analogy with the dipole potential in an infinite homogeneous conductor, the potential of a hypothetical generator is assumed to be inversely proportional to the squared distance between the imaginary measuring point and projection of the generator onto the same axis.

Then the potentials at the imaginary measuring points on the semiaxes *x'*, *y'*, *z'* are defined by the expressions

$$\varphi_{+x'} = K_{x'}/(r_{x'} - x'_G)^2, \qquad \varphi_{-x'} = K_{x'}/(r_{x'} + x'_G)^2,$$
$$\varphi_{+y'} = K_{y'}/(r_{y'} - y'_G)^2, \qquad \varphi_{-y'} = K_{y'}/(r_{y'} + y'_G)^2,$$
$$\varphi_{+z'} = K_{z'}/(r_{z'} - z'_G)^2, \qquad \varphi_{-z'} = K_{z'}/(r_{z'} + z'_G)^2 \qquad 2.$$

where x'_G, y'_G, z'_G are coordinates of the hypothetical generator and $K_{x'}, K_{y'}, K_{z'}$ are constants. On the basis of these equations, the following expressions for the coordinates of the hypothetical generator are formulated:

$$x'_G = r_{x'}p_{x'} + \Delta_{x'}, \quad y'_G = r_{y'}p_{y'} + \Delta_{y'}, \quad z'_G = r_{z'}p_{z'} + \Delta_{z'} \qquad 3.$$

where

$$p_{x'} = \frac{\sqrt{\varphi_{+x'}} - \sqrt{\varphi_{-x'}}}{\sqrt{\varphi_{+x'}} + \sqrt{\varphi_{-x'}}}, \quad p_{y'} = \frac{\sqrt{\varphi_{+y'}} - \sqrt{\varphi_{-y'}}}{\sqrt{\varphi_{+y'}} + \sqrt{\varphi_{-y'}}}, \quad p_{z'} = \frac{\sqrt{\varphi_{+z'}} - \sqrt{\varphi_{-z'}}}{\sqrt{\varphi_{+z'}} + \sqrt{\varphi_{-z'}}} \qquad 4.$$

and $\Delta_{x'}, \Delta_{y'}, \Delta_{z'}$ are the additive corrections.

After calculating the generator coordinates by equations 3, the position of the midplane, which is perpendicular to the heart vector, can be found. This position is defined by the point of intersection of the midplane with the heart vector. The shift of this point with respect to the coordinate origin is

$$d = d_G \cos\xi, \qquad 5.$$

where d_G is the distance of the hypothetical generator from the coordinate origin and ξ is the angle between the heart vector and radius vector of the generator. When taking into account equation 3, the last equation gives

$$d = l_{x'}(p_{x'}r_{x'} + \Delta_{x'}) + l_{y'}(p_{y'}r_{y'} + \Delta_{y'}) + l_{z'}(p_{z'}r_{z'} + \Delta_{z'}) \qquad 6.$$

where $l_{x'} = D_{x'}/D,\ l_{y'} = D_{y'}/D,\ l_{z'} = D_{z'}/D$ are the direction cosines of the heart vector.

The exact position of the midplane is defined by the point of its intersection with the heart vector at the distance from the coordinate origin

$$d'_c = x'_c l_{x'} + y'_c l_{y'} + z'_c l_{z'} \qquad 7.$$

where x'_c, y'_c, z'_c are the assumed coordinates of the ischemic lesion center. Then the error of calculated midplane position is

$$\delta = d - d'_c \qquad 8.$$

Optimal values of parameters $r_{x'}, r_{y'}, r_{z'}, \Delta_{x'}, \Delta_{y'}, \Delta_{z'}$ are determined with the use of the aforementioned mathematical model of the cardiogenerator and body.

Results and Discussion

On the basis of the interactive mathematical model described in (4, 5), acute ischemic lesions of subendocardial (En) and subepicardial (Ep) myocardium were assigned with various localizations. In particular, localizations in the lateral left ventricular wall (LEnL and LEpL), lateral right ventricular wall (LEnR and LEpR), left side of the septum (SEnL), and right side of the septum (SEnR) were considered.

For each lesion localization (with given values of x'_c, y'_c, z'_c), unipolar electrocardiograms at the points I, E, C, A, M, H, F, R, L were obtained for one heart cycle and potentials $\varphi_I, \varphi_E, \varphi_C, \varphi_A, \varphi_M, \varphi_H, \varphi_F, \varphi_R, \varphi7_L$ were assumed to be the averaged electrocardiosignals during the initial 35 ms interval of the ST period. These values made up the training data sample for determination of the correction parameters in equation 6.

At first, assuming the spatial shift errors for various lesions to be sufficiently close, averaged additive corrections $\Delta_{x'}, \Delta_{y'}, \Delta_{z'}$ were found for considered lesions in the model, where positions of the imaginary measuring points are defined by the transversal radius of the standard chest

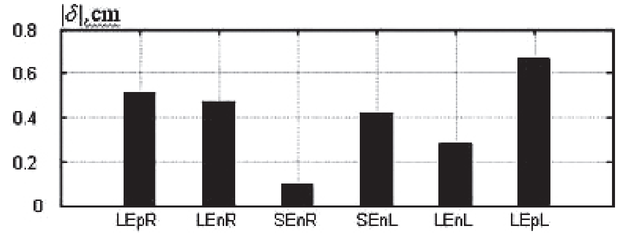

Figure 3 Absolute values of the midplane position errors for various localizations of the ischemic lesions
LEpR – Right ventricular lateral subepicardial region, LEnR – Right ventricular lateral subendocardial region, SEnR – Right ventricular subendocardial side of the septum, SEnL – Left ventricular subendocardial side of the septum, LEnL – Left ventricular lateral subendocardial region, LEpL – Left ventricular lateral subepicardial region

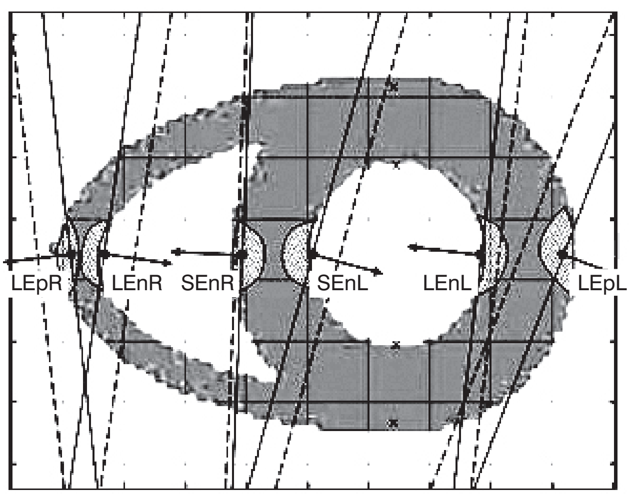

Figure 4 Lines of intersection of the midplanes for various ischemic lesions with the transverse cross-section of the heart ventricles passing through the centers of the lesions considered. The lesion regions are filled with dots; arrows approximate the directions of heart injury vectors. The true and calculated positions of the midplanes are indicated by the solid and dashed lines, respectively. LEpR – Right ventricular lateral subepicardial region, LEnR – Right ventricular lateral subendocardial region, SEnR – Right ventricular subendocardial side of the septum, SEnL – Left ventricular subendocardial side of the septum, LEnL – Left ventricular lateral subendocardial region, LEpL – Left ventricular lateral subepicardial region

model, $r_{x'} = r_{y'} = r_{z'} = a/2 = 13.5$cm. Then, by minimizing the mean square error δ, the refined values for the coefficients $r_{x'}$, $r_{y'}$, $r_{z'}$ were calculated. Finally, the following values were obtained: $r_{x'} = 14.8$ cm, $r_{y'} = 10.9$ cm, $r_{z'} = 11.1$ cm, $\Delta_{x'} = -1.4$ cm, $\Delta_{y'} = -0.4$ cm, $\Delta_{z'} = 0.5$ cm.

The resulting errors of the midplane position are presented in **Figure 3**. In most studied cases, the midplane is situated rather close to the boundary of the ischemic lesion and its displacement from the lesion center does not exceed 0.7 cm.

Midplane positions determined for various localizations of the ischemic lesion are illustrated in **Figure 4**.

Results of the described model study show that the position of the midplane is rather sensitive to the spatial localization of the lesion. On the whole, the method correctly indicates this localization for the lesions oppositely situated in the left and right ventricles, when the heart injury vector lies closely to the line normal to the lateral surfaces of the ventricles. For the lesions at the most anterior and most posterior positions, when the injury vector lies closely to the sagittal axis of the chest, the error is greater and the described technique should be respectively modified. After further verification of the presented method on patients with acute ischemia, it may be used for revealing the parts of the heart containing injured regions. One of the advantages of the method is the rather simple measuring procedure, which causes no complication when compared to the commonly accepted electrocardiographic or vectorcardiographic investigation. The limitation of the method is its applicability mainly for cases of isolated (not multiple) injured areas. It is desirable to use for measurements only the equipment with characteristics providing correct reproduction of the ST potentials.

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