INVESTIGATION OF A MOVABLE MULTIPOLAR EQUIVALENT GENERATOR OF THE HUMAN HEART

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One of the most important aspects of modern electrocardiography is establishment of the relationship between the distribution of potential on the body surface and the equivalent generator creating it. This problem has an infinite number of solutions, and one result of this is the existence of a large number of variants of equivalent generator of the heart. However, only for one of them has the reverse problem been most satisfactorily solved [6]. This equivalent generator is an equivalent generator of multipolar type fixed at one point. In investigations to study this type of generator, fixed at the anatomical center of the heart, fairly consistent results were obtained, but they showed that dipole approximation was too approximate. It was also found that the addition of multipolar expansion of the quadrupole to the dipole term does not give the desired increase in accuracy of description of the electric field of the heart [3, 4, 8, 9]. However, despite the fact that the real cardiac generator is not a simple dipole, for any fixed moment of the cardiac cycle it is possible to find a point such that, if the multipolar equivalent generator is located there, dipole approximation will be closest. This point is usually called the electrical center of the heart [5, 7]. Since the structure of the cardiac generator undergoes regular changes during the cardiac cycle, the position of the electrical center also naturally will change. The trajectory of its movement was described in [2].

It is interesting to study how the accuracy of dipole and dipole–quadrupole approximation of the human body surface ECG potential is increased if a movable model of the equivalent generator is used in which the point of its application coincides with the electrical center of the heart and moves along its trajectory. The investigation described below was devoted to the study of this problem.

EXPERIMENTAL METHOD

An investigation was conducted on six healthy subjects and three patients with an aneurysm of the left ventricle after myocardial infarction. The method used was to record the ECG in 80 unipolar leads, the electrodes of which were uniformly distributed over the surface of the patients' chest, and to obtain data on the momentary distribution of the ECG potential every 5 msec in the course of the QRS complex, T wave, and ST segment (for patients in whom this did not fall on the isoelectric line). The human body was regarded as a homogeneous isotropic conductor* with specific electrical conductance of $2 \cdot 10^{-3}\ \Omega^{-1} \cdot cm^{-1}$, and the cylindrical coordinates of the points of the leads were determined relative to the center of a transverse section through the body at the level of the 5th intercostal space. The aim of subsequent analysis of the data was to determine the following values for each of the 40 moments of the cardiac cycle:

a) the contribution of dipole and quadrupole components to the surface potential for two immovable equivalent generators fixed at the geometric center of the torso and at the geometric center of the heart†;

*It is not yet possible to allow for internal nonhomogeneity of the body. However, this simplification is acceptable, for the errors due to it are most probably systematic in character [1].

†The coordinates of the geometric center of the heart were determined from roentgenograms in two projections.

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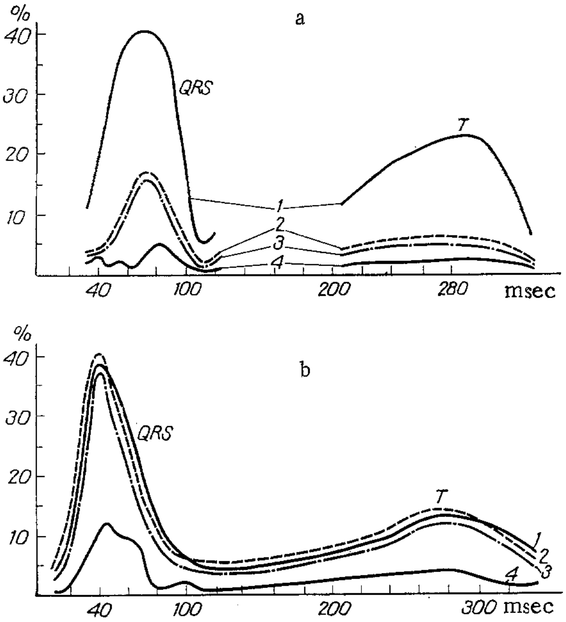

Fig. 1. Changes in mean square contributions during cardiac cycle: 1) of dipole (φ_D) and 2) quadrupole (φ_Q) for an equivalent generator fixed at the geometric center of the torso; 3) of the quadrupole for an equivalent generator fixed at the geometric center of the heart; 4) of the quadrupole for a movable generator. a) Data from investigation of healthy subject, b) of patient.

b) the coordinates of the electrical center of the heart;

c) the contribution of quadrupole components for the equivalent generator moving along the trajectory of the electrical center of the heart.

In order to realize the methodologic approach described above, mathematical expressions obtained on the basis of the theory given in [5,7] were used. As applied to this problem of immovable equivalent generators, fixed at geometric centers of the torso and heart, the multipolar components are expressed in the general form as follows:

$$\left.\begin{matrix} a_{nm} \\ b_{nm} \end{matrix}\right\} = \gamma \frac{\varepsilon_m (n-m)!}{(n+m)!} \int \varphi_S \operatorname{grad} \left[r^n P_n^m (\cos\theta) \left\{ \begin{matrix} \cos m\psi \\ \sin m\psi \end{matrix} \right\} \right] dS, \quad (1)$$

where γ is the specific electrical conductance, φ_S is the potential on the surface of measurement (the chest wall), r the distance to this surface from the origin of coordinates (from the geometric center of the torso and the geometric center of the heart, respectively); $P_n^m \times (\cos\theta)$ the associated Legendre polynomial of the n order and to the m power ($\varepsilon_m = 1$ when m = 0 and $\varepsilon_m = 2$ when $m \neq 0$). Integration is carried out on the surface of measurement S.

Three components of the dipole (D), namely a_{11}, b_{11}, and a_{10}, and five independent components of the quadrupole (Q), namely a_{20}, a_{21}, b_{21}, a_{22}, b_{22}, can easily be obtained by equation (1). Their values were calculated for each of the above-mentioned equivalent generators, respectively. Coordinates of the electrical center of the heart (x_0, y_0, z_0) were then determined by minimization of the contribution of quadrupole components to the surface potential. If the point of application of the equivalent generator at each moment of the cardiac cycle is made to coincide with the electrical center of the heart, a movable equivalent generator is obtained, for which new quadrupolar components were calculated. For each of the equivalent generators considered here, values of the mean-square potential were calculated from multipoles of different orders in the surface potential.

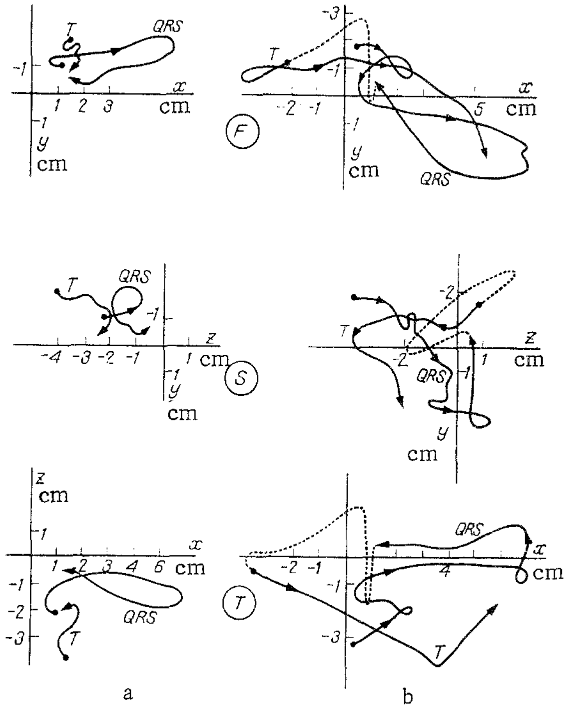

Fig. 2. Characteristic trajectories of movement of the electrical center of the heart in the course of the QRS complex, T wave, and ST segment (broken curve) for a healthy subject (a) and patient (b) in three projections on the frontal (F), left sagittal (S), and transverse (T) planes.

EXPERIMENTAL RESULTS

The results obtained by the use of the method of calculation given above were also used as a criterion for evaluating the accuracy of approximation of the electrical field of the heart by the three equivalent generators examined above. Curves showing changes in the mean-square contribution of the dipole (φ_D) for an equivalent generator fixed at the geometric center of the torso, and the mean square contribution of the quadrupole for all three equivalent generators (φ_Q, φ_{QN}, φ'_Q) are given in Fig. 1a, b. The results of investigation of a healthy subject are given in Fig. 1a and results of investigation of a patient with an aneurysm of the left ventricle after myocardial infarction in Fig. 1b. It will be clear from Fig. 1 that the values of the contribution of the quadrupole for the two immovable equivalent generators fixed at the geometric centers of the torso (φ_Q) and heart (φ_{QN}) are of the same order. However, on the transition to a movable model the value of the quadrupole contribution is significantly reduced (φ'_Q) and, consequently, the accuracy of dipole approximation of the electrical field of the heart is considerably increased. It should also be noted that this phenomenon takes place much more noticeably in pathology, when the inadequacy of the purely dipole approximation is demonstrated particularly acutely. This indicates yet another advantage of the movable model, namely that it can approximate equally accurately the electrical field of the heart in both healthy and pathological cases. This is because the movable model enables the examination to be confined to the dipole component, for in this case the multipole series converges more rapidly and the information of the quadrupole contribution to the immovable model (which, moreover, is very difficult to link with the structure of the real heart generator) is represented in the movable model by the trajectory of movement of the electrical center of the heart. In this form, this information clearly reflects the basic features of the electrical process of excitation in the heart and, consequently, it is more closely linked with its anatomical and physiological state.

When a movable multipolar equivalent generator is used, therefore, only six parameters are needed to characterize the electrical process of excitation in the heart quite fully, and these parameters are independent of extracardiac factors. Three of them are curves showing the change in dipole components during the cardiac cycle and they coincide with an accuracy amounting to a constant coefficient with ideally corrected orthogonal leads. The remaining three curves are the trajectory of movement of the electrical center of the heart in three projections on the frontal (F), sagittal (S), and transverse (T) planes (Fig. 2a, b) which, as has been stated above, contain nondipole information absent in corrected orthogonal leads.

Consequently, the model of a movable multipolar equivalent generator, whose point of application moves along the trajectory of movement of the electrical center of the heart, merits the closest study and is a very promising tool for the solution of diagnostic problems.

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