PRACTICAL ECG MAPPING WITH FEW-LEAD SYSTEMS: A NEW APPROACH AND MATHEMATICAL MODELING

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Three versions of practical system for ECG mapping with extremely small number of leads are considered. The chosen version is primarily intended for noninvasive cardiac potential mapping on a spherical surface enclosing the heart (imaging sphere). Using the simplified mathematical models of the chest as bounded volume conductor and heart as bioelectric generator, it is shown that the lead system with 12 unipolar leads situated rather conveniently for practical investigations provides maps closely approximating the accurate maps that could be obtained by multiple-lead mapping.

1. Introduction

The main advantages of ECG mapping methods over the standard ECG technique are the higher diagnostical informativity and possibility to represent the data in a topographic form, which facilitates quantitative and heuristic analyses of the obtained information. In spite of the fact that the ECG mapping techniques have been completely mastered and are regularly applied in some large cardiology institutions, a more widespread use of them has slowed down, primarily because of the expensiveness and labour-consuming nature of such investigation. Here we present the results of mathematical modeling of more practicable systems based on the classical Frank electrode configuration supplemented with few additional electrodes.

2. Subject and methods

The lead electrode configurations considered include the following electrodes (Fig. 1, left): system FRAM 1, the classical Frank electrodes I, E, C, A, M, H, F with two additional electrodes R and L on the arms; system FRAM2, the FRAM1 electrodes with two additional electrodes G and B on the front and back chest surfaces above the electrodes E and M, respectively, at the distances from them equal to half the sagittal chest diameter; system FRAM3, the FRAM2 electrodes with two additional electrodes K and N equidistantly located between the Frank electrodes I and E, A and M, respectively. The potentials are measured synchronously in the unipolar manner for each electrode with respect to the right arm, then unipolar signals with respect to the Wilson terminal (or a specially averaged zero potential) are calculated. The coordinates of the electrodes are defined according to a realistic geometrical model of the chest individually adapted for the investigated person on the basis of measuring the following anthropometric parameters: left-to-right (transversal) diameter a, back-to-front (sagittal) diameter b, and height h. In practice, it is reasonable to use the same typical relations between these parameters for all the subjects, putting $b = \left(\sqrt{2}/2\right)a$ and $h = \sqrt{2}\,a$. The heart midpoint (the coordinate origin) is assumed to be shifted by $0{,}1a$ to the left and forward with respect to the chest midpoint.

The body surface potential distribution is approximated by the sum of several terms in the form of spatial spherical harmonics analogous to the lower-order terms of the classical multipole expansion of potential field in the Cartesian coordinate system xyz with the origin at the midpoint (geometric center) of the heart (method of adaptive quasimultipole approximation of potential, AQMAP [1].)

The coefficients A'_{nm}, B'_{nm} (quasimultipole components) of the approximating potential expansion φ are determined by solving a system of linear equations of the following form with the use or the least-squares method:

$$K\left[\frac{1}{r_i}A'_{00} + \frac{z_i}{r_i^3}A'_{10} + \frac{x_i}{r_i^3}A'_{11} + \frac{y_i}{r_i^3}B'_{11} - \frac{1}{2r_i^5}\left(x_i^2 + y_i^2 - 2z_i^2\right)A'_{20} + \frac{3x_iz_i}{r_i^5}A'_{21} + \frac{3y_iz_i}{r_i^5}B'_{21} + \right.$$
$$\left. + \frac{3}{r_i^5}\left(x_i^2 - y_i^2\right)A'_{22} + \frac{6x_iy_i}{r_i^5}B'_{22}\right] = \varphi_i, \qquad (1)$$

where K is a constant, φ_i is the potential, x_i, y_i, z_i are the coordinates, and $r_i = \sqrt{x_i^2 + y_i^2 + z_i^2}$ is the distance from the coordinate origin of the electrodes indicated by the subscripts i = I, E, C, A, M, H, F, R, L, G, B, K, N. For the system FRAM1, the quasimultipole components A'_{21} and B'_{21} are neglected, so there are 9 equations with 7 unknowns $A'_{00}, A'_{10}, A'_{11}, B'_{11}, A'_{20}, A'_{22}, B'_{22}$. For the systems FRAM2 and FRAM3, all the quasimultipole components in (1) are used, so there are 11 and 13 equations, respectively, with 9 unknowns.

The potential $\varphi(x,y,z)$ at any body surface (BS) point is defined by the left side of equation (1) after substituting the found values of the quasimultipole components A'_{nm}, B'_{nm} and the coordinates x,y,z of the point under consideration. Then, using the aforementioned simplified chest model, the true multipole components of the three lower orders (dipole, quadrupole, and octupole components) are calculated by the well-known relations including weighted integration of the potential over the chest surface (the same coordinate system with the origin at the heart center is used) [1]. The multipole components found are used to determine the potential distribution on the standard imaging surface (SIS) enclosing the heart, in particular, on a sphere with a given radius R and center at the coordinate origin (Fig. 1, right). Under assumption of the infinite homogeneous conducting medium, this distribution is calculated, according to the multipole theory, as follows:

$$\varphi = \frac{1}{4\pi\sigma} \sum_{n=1}^{3} \sum_{m=0}^{n} R^{-n-1} P_n^m(\cos\,\theta)\left(A_{nm} \cos m\psi + B_{nm} \sin m\psi\right), \qquad (2)$$

where θ, ψ are the angular spherical coordinates of the SIS points, P_n^m is the associated Legendre function of the first kind, nth degree and mth order (n and m are nonnegative integers), and $P_n^0 = P_n$ is the Legendre polynomial.

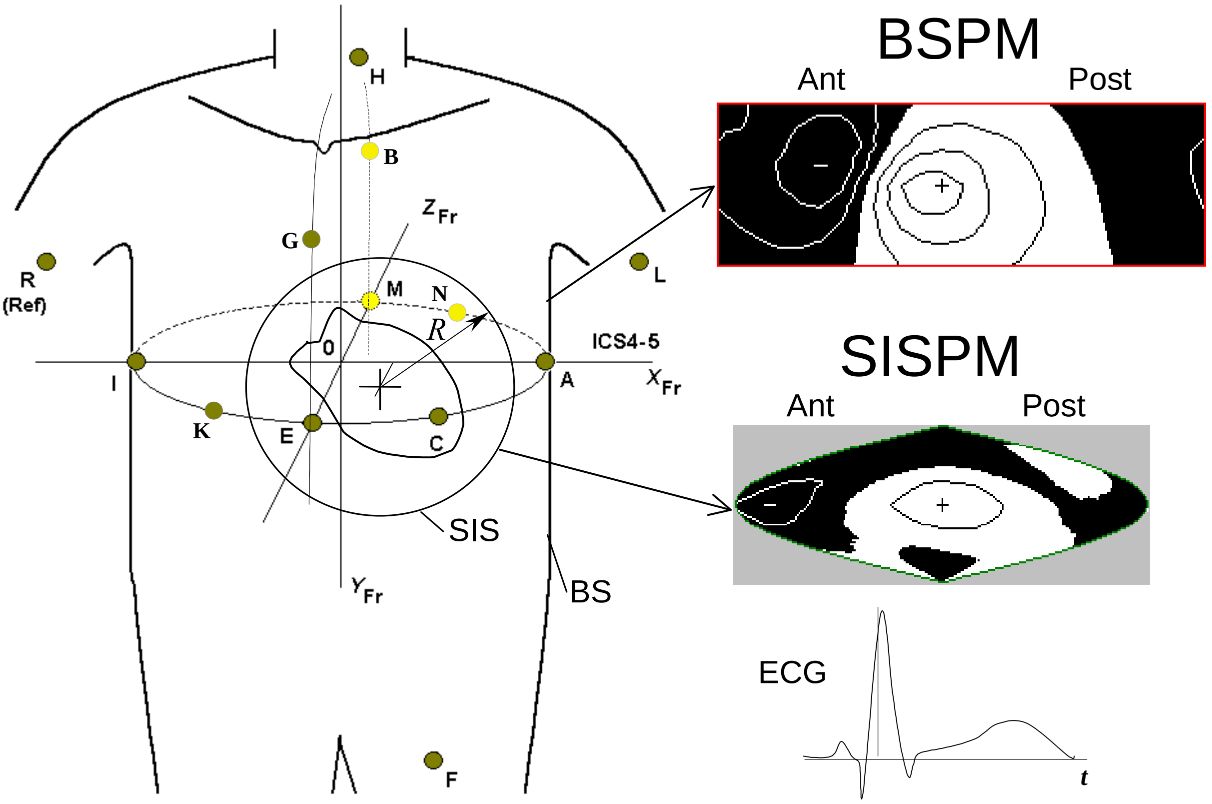

Fig. 1. Lead electrode set-up and potential maps (BSPM and SISPM) for a time instant indicated on ECG under the maps.

To decrease the distortions of the potential distribution shape resulting from too small number of the multipole terms used, the optimal value of R should be chosen (it was shown to be about half the transversal size of the chest).

To estimate the accuracy of the described method depending on the aforementioned lead systems, it was investigated by mathematical modeling on a simplified chest model having the parallelepipedal shape [2], with dimensions equal to the main anthropometric parameters a, b, and h. For this model, analytical expressions were obtained to calculate the surface potential for a point dipole with arbitrarily given moment and spatial position. Thus, the forward electrodynamical problem could be solved for any configuration of the model cardiac generator, consisting of deliberately arranged dipoles in the heart region of the chest model, and the electrode potentials could de determined. Then the inverse problem formulated above, that is determination of the potential distribution on the SIS could be implemened. Such modeling was carried out for several typical structures of the elementory bioelectric generator of the heart, including dipole and quadrupole structures, and the homogeneous parallelepipedal model.

3. Results

Some results of the model study are presented in Fig. 2. At the left, the dipole generators (bold arrows) are shown in the heart region (bounded by the dashed circle), in particular: *a*, central axial dipoles D_x, D_y, D_z and diagonal dipole D_{xy} at the point (0, 0, 0); *b*, shifted axial dipoles D_x, D_y, D_z at the point (0,1a, 0, 0); *c*, pairs of oppositely directed axial dipoles shifted by 0,05a with respect to the origin on the axes x, y, and z (axial quadrupole structures Q_x, Q_y, Q_z , respectively). To the right of the generator models, the potential maps on the standard imaging surface (SISPM) for each generator configuration are shown. The SIS is cut along the right meridian (in the $x0z$ plane), unrolled, and projected onto the plane in the equiareal projection format. The exact potential maps (calculated under assumption of infinite homogeneous conducting medium) and the maps obtained by the lead systems FRAM1, FRAM2, and FRAM3 with the chest model described are presented.

It is seen that the maps obtained by the investigated practical lead systems retain the main features of the true potential distribution, in particular, extension and situation of the positive and negative regions, relations between the extrema, and so on, while the system FRAM3 provides the most efficient approximation of the potential distribution, as would be expected according to the number of electrodes used.

4. Conclusions

The SISPM with the use of the lead system FRAM3 and technique proposed offers some properties which favourably distinguish it from the scalar ECG, VCG, and BSPM. In particular, the data are presented in a map-like form closely related to the anatomical parts of the heart, therefore, the visual (heuristic) analysis of them is more efficient; the effects of the eccentric position of the heart in the chest and of the body surface shape on the measured potential field are significantly lowered; the measurement procedure is extremely simple as compared to the common multiple-lead BSPM.

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References

1. Titomir L.I., Kneppo P. Bioelectric and Biomagnetic Fields. Theory and Applications in Electrocardiology. Boca Raton etc., CRC Press, 1994.
2. Rush S., Ricca A., Sala M., Taccardi B. Multiple peaks from a single dipole in a homogeneous torso model. – In: Body Surface Mapping of Cardiac Fields, Ed. by Rush S. and Lepeschkin E., Basel etc., S. Kager, 1974, p. 89–93.

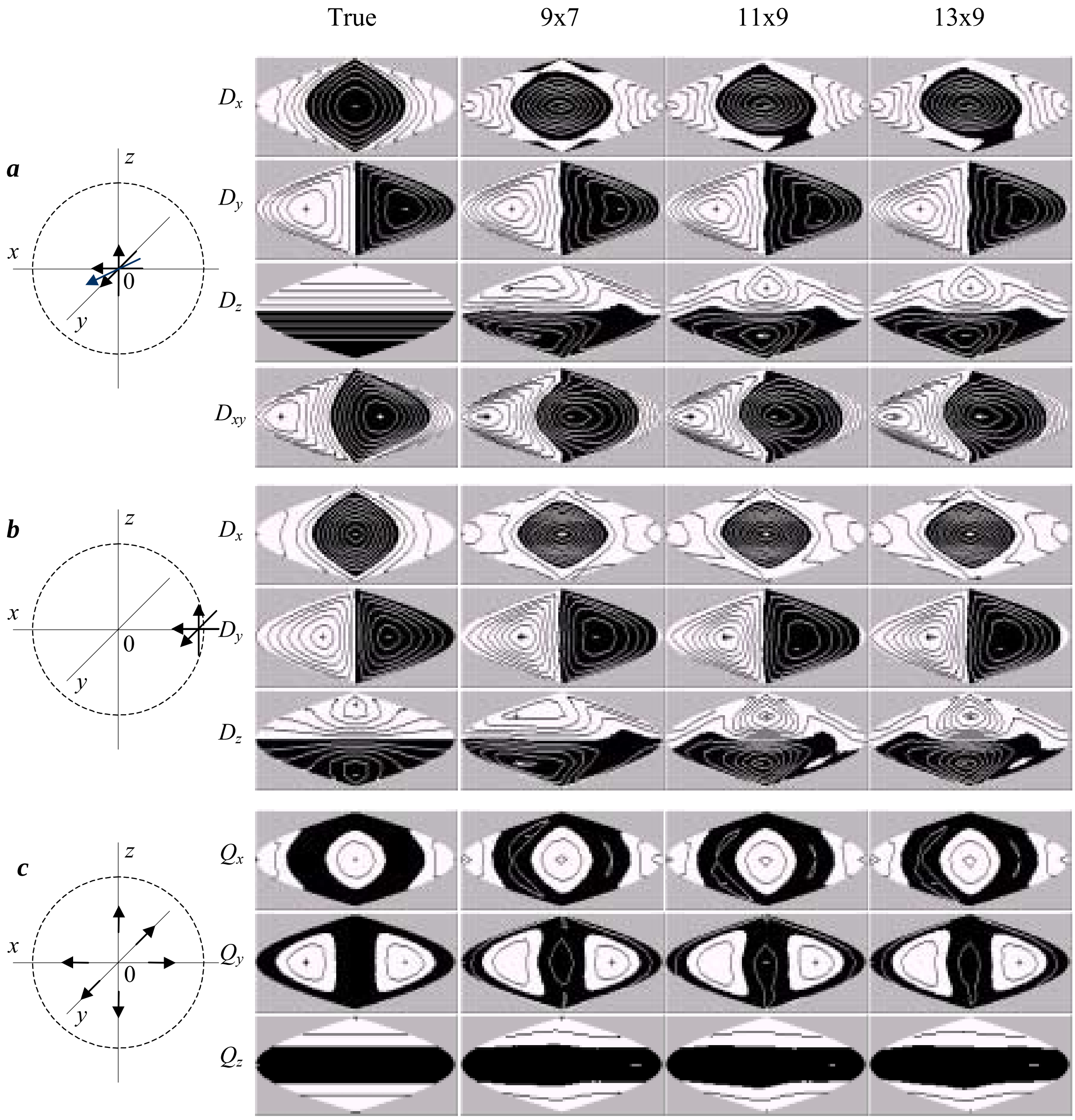

Fig. 2. Model generator configurations (left) and corresponding SISPM obtained by exact calculation (True) and by using the lead systems FRAM1 (9x7), FRAM2 (11x9), and FRAM3 (13x9). All potential values are normalized by the maximum potential of the central radial dipole, the interval between the equipotentials is 0,2.