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Computer Processing of the Orthogonal Electrocardiogram and Vectorcardiogram

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Summary

The aim of this contribution was to review the possibilities of presentation of orthogonal ECG signals and to evaluate the progress in computerized electrocardiography achieved in Czechoslovakia. The information about the cardiac electric field in orthogonal electrocardiography is defined and consequently displayed as a fixed single dipole (vector). The spatial trajectory of vector end-point (spatial vectorcardiographic loop) can be presented in different ways – as orthogonal electrocardiogram, polarcardiogram, planar vectorcardiogram and decartogram, respectively. The advantages of particular methods of presentation, as well as their limitations are discussed. Computer-assisted electrocardiography was introduced in Czechoslovakia in 1974. The original AVA program has been further developed in the Research Institute of Medical Informatics (formerly Research Institute of Medical Bionics). The currently developed system CardioSys allows the utilization of all the possibilities of orthogonal ECG and vectorcardiographic presentation for clinical and epidemiological cardiology as well as for the research.

Key words

Orthogonal Electrocardiography – Vectorcardiography – Computer analysis

The electrographic signal provides irreplaceable information about the status and activity of the heart. In current clinical practice, it is mostly registered by means of a standard 12-lead ECG system. However, the information obtained in this way is characterized by a considerable redundancy. Orthogonal physically corrected electrocardiographic lead systems have the following advantages with respect to the standard 12-lead ECG (Ruttkay-Nedecký 1983): a) they do not contain redundant information, so that manual evaluation as well as computer processing of ECG is more efficient, b) spatial presentation in the X, Y, Z coordinate system is in accordance with the usual description of the patients body, as for example on X-ray or physical examination, c) the information content of orthogonal ECG is not smaller than that of the standard 12-lead ECG, d) the relations between individual leads can be determined in more detail and visualized. This advantage is provided by vectorcardiography.

The aim of this contribution was to review the possibilities of displaying orthogonal ECG signals and to evaluate the progress in computerized electrocardiography achieved in the Czech and Slovak Republics.

The temporospatial distribution of myocardial activation fronts and the pattern of this repolarization are the physiological source of electrocardiographic potentials. The front of myocardial depolarization is in fact an electrical double-layer and, as such, may be represented by a set of regularly spaced unit vectors. The vectorial sum of these unit vectors gives the instantaneous cardiac vector, which is recorded as an instantaneous vectorcardiographic vector by means of appropriate physically corrected lead systems (Frank 1956, McFee and Parungao 1961, Laufberger 1965). The trajectory of the end-points of these instantaneous vectors in space results in the spatial vectorcardiographic loop. While distinct activation fronts may be experimentally recorded in the myocardium of atria and ventricles during depolarization, the situation during the repolarization period is more complicated because of spatial dispersion of boundaries between areas of the myocardium with different levels of repolarization.

The crucial problem of non-invasive assessment of the cardiac electric field is to find how to express the underlying physiological events in the myocardium of body surface potential measurements in a meaningful and quantitative manner.

Hitherto, the best and most rational solution is spatial vectorcardiography (Rijlant 1956, Laufberger 1965, Kowarzyk *et al.* 1970).

The spatial trajectory of vector end-points (spatial vectorcardiographic loop) can be defined and presented in the following ways:

1. Orthogonal electrocardiograms represent the time functions of X,Y,Z rectangular coordinates of spatial vector end-points. Their presentation and evaluated parameters (amplitudes and time intervals of P,Q,R,S,T waves) are the same as in standard 12-lead electrocardiography, so they are easily acceptable for users who are familiar with the rational evaluation of standard 12-lead ECGs. Furthermore, orthogonal electrocardiograms are needed for the study of cardiac arrhythmias.
2. Polarcardiograms describe the spatial magnitude (module) and spatial orientation of vector end-points as a time course of polar coordinates, e.g. spatial magnitude, azimuth and elevation. The polarcardiogram provides a good description of the trajectory in space. However, in both cases we obtain the time courses of three coordinates and their mutual relationships at any given instant are difficult to identify.
3. This problem is solved by vectorcardiography. Planar vectorcardiograms are the planar projections of the spatial vectorcardiographic loop onto three planes perpendicular to each other – frontal, sagital and horizontal. This presentation is very instrumental for visualization of activation front sequence, and provides a broad spectrum of two- and three-dimensional parameters. They provide complex detailed information about the spatial localization and movement of spatial vector end-points.
4. Decartograms (as will be described below) visualize the sequence of activation as a sequence of activated points on a spherical surface closely enveloping the heart. The localization of the activated areas determined by spatial orientation of the vector, and the extent of the activated area at given instants of time is proportional to the module of the vector related to the maximum spatial vector magnitude. Decomposition of the information about the spatial localization of a vector end-point into the area of defined localization and size makes it possible to use advanced mathematical methods, which is especially important in the evaluation of normal and borderline pathological findings.

For practical purposes of preventive and clinical cardiology, different computer-based automatic data evaluation and diagnostic programs have been devised. Computer assisted electrocardiography was introduced in Czechoslovakia in 1974 when the Research Institute of Medical Bionics in Bratislava was equipped with computers allowing the introduction and mutual comparison of the 12-lead ECG 5600 interpretative system (Balda 1977) and the orthogonal 3-lead system ECG 1530 B, (AVA interpretative system) (Pipberger 1974). At that time, the AVA system was selected for utilization in preventive cardiologic health programs since it was found that computer processing of physically corrected orthogonal ECG leads was more rational and more apt for further development. The AVA software was implemented into home produced computers and a series of ECG apparatuses produced by Chirana (Prague) was adapted for this purpose.

The diagnostic efficiency of the AVA interpretative program, based on vectorial analysis of the orthogonal 3-lead ECG signals, was repeatedly reevaluated (Table 1)

Table 1
Brief summary of diagnostic evaluation of AVA program in Czechoslovakia giving year of evaluation, computer employed, reference electrocardiologic method and % of false positive (FP) and false negative (FN) findings

1976 (Ruttkay-Nedecký)	HP 2100, compared to 12-lead ECG FP 33.1 %	FN 7.7 %
1982 (Renker *et al.*)	RPP 16, compared to 12-lead ECG FP 34.7 %	FN 2.9 %
1988 (Bachárová *et al.*)	SM 4-20, compared to VCG FP 10.1 %	FN 4.5 %

The first evaluation of the software implemented on a HP 2100A computer was performed in 1975 (Ruttkay-Nedecký 1976). Full diagnostic agreement with the conclusions of human readers of 12-lead ECG was obtained in 56.5 % of ECGs. False positive conclusions were described in 33.1 %, false negative in 7.7 % (4.3 % incomplete right bundle branch block, 1.7 % abnormal P wave configurations, 1.7 % non-specific ST-T changes). The first Czechoslovak equipment used for computerized ECG analysis was a minicomputer RPP 16 combined with an electrocardiograph Chirakard 601 TK. A group of 167 ECGs was analyzed resulting in 34.7 % of false positive and 2.9 % of false negative conclusions as compared to 12-lead ECG evaluation by cardiologists (Renker *et al.* 1982). Evaluation of 488 ECGs within the framework of a screening project showed 10.1 % of false positive and 4.5 % of false negative conclusions when compared with the assessment of vectorcardiograms obtained from the same signal by experienced vectorcardiographers (Bachárová *et al.* 1988).

The repeat variability and correlations between changes in 16-lead orthogonal Frank ECG parameters were examined in 50 healthy subjects, 50 patients with left ventricular hypertrophy (LVH) and 50 patients with anterior or posterior chronic myocardial infarction. The greatest effect on QRS-T diagnostic probability was exerted by changes of amplitudes of Ry, Ty, Jy, Rz, time intervals Qx and

QRS in the normal group, amplitudes Rx, Tx, Ty, Jz and Qz duration in patients with LVH, amplitude ratio Q/Ry, Q/Rz and QRS duration in patients with myocardial infarction. Changes of the probability values could only be partially predicted from changes of ECG values. Shortlasting repeat variability of the ECG parameters using SM 3-20 minicomputer was found to be very low (Bachárová *et al.* 1975).

Results obtained with the AVA program implemented by Czechoslovak measurement and computer techniques were comparable with published data.

In spite of the above listed advantages of the AVA program, its acceptance by physicians has been limited, since they had following difficulties in the decision making process.

In order to improve the acceptability of vectorcardiographic interpretative programs, the orthogonal ECG signals were processed and visualized in addition to the AVA software output in two ways: (i) as planar projection of vectorcardiograms, and (ii) as dipolar electrocardiograms.

Frank's electrocardiograms were processed in a group of 482 unselected subjects as well as in a group of 448 patients with cardiac pathology by the AVA program. The group of subjects with normal findings was defined by a lack of abnormal diagnostic statements of the AVA program. In this group, parameters of instantaneous QRS vectors at 10 ms time intervals from the onset of QRS were used for constructing spatial vector end-points projected onto the horizontal and left sagital planes. Only 34.1 % of ECGs evaluated as normal by the AVA program in the group of unselected subjects and 11.2 % ECGs in the group of cardiac patients, respectively, were found to have all instantaneous QRS vector end-points within normal reference areas. These results underline the problem of borderline abnormality of vectorcardiographic parameters which remains unapparent if the classification is made only by exclusion of pathological features or by classifying whether the subject fits into normal reference parameters or not (Bachárová *et al.* 1987).

In dipolar electrocardiotopography (DECARTO), orthogonal ECG signals are transformed by means of a simple mathematical model (Ruttkay-Nedecký *et al.* 1988, Titomir and Ruttkay-Nedecký 1987) to represent the equivalent generator of the cardiac electric field as a uniform double-layer with varying time and localization on a spherical surface approximating the ventricular wall, called the image sphere. Ventricular activation is represented by sequential maps of activated points on the image surface. More compact, but also easily comprehended visualization of the same data may be obtained in the form of summary maps of cardiac excitation, or chronotopocardiograms. Decartograms are presented in the form of discrete spherical image surface in the shape of a rectangle.

A sample of 123 healthy subjects, originally included in a study of normal vectorcardiographic variability (Bachárová and Melotová 1986) served for constructing probability topograms of the activation sequence represented on a spherical image surface (Bachárová 1986, Bachárová *et al.* 1991). The localization of areas of activation with $p>0.05$ probability were in good agreement with the localization of positive potential distribution on body surface potential mapping in a healthy subject (Taccardi 1963). Areas of maximum probability moved, during ventricular depolarization, from the right paramedial mid-area to the left, downwards and posteriorly, which is in good agreement with the myocardial activation sequence as represented by the spatial vectorcardiogram, as well as with the experimental data on the current field measured in the close vicinity of the isolated dog heart (Taccardi *et al.* 1972).

An ordinary set of discrete elements (points) on the image surface may be treated as consisting of two fuzzy subsets at any instant time, those of activated and those of non-activated elements (Ruttkay-Nedecký 1992). If each element of the reference spherical surface is attributed the probability of being activated at a given instant of time as its characteristic membership function, we obtain the reference fuzzy subset of activated elements at time t. The cardiac electric activity of a subject may then be expressed as a time series of fuzzy subsets, each representing the activated elements of the spherical image surface at a predetermined instant of time with membership functions obtained from the reference fuzzy subset. After having computed individual sums of membership functions in our reference sample for each 10th millisecond of QRS duration, we may define the criteria of normality in terms of fuzzy mathematics.

Visualization of physically corrected orthogonal ECG lead signals as vectorcardiographic loops and determination of the spatial localization of instantaneous vector end-points enables the physician to find the bridge in his conceptual model between the characteristics of myocardial activation propagation and the abstract representations of the cardiac electric field. Treatment of the same signals as dipolar electrocardiotopograms aids in finding topographical relations between body surface electrical events and the activation process in the myocardium. This approach also aids in understanding and analysis of body surface potential maps obtained by separate procedures.

In conclusion, ECG diagnostic computer programs based on vectorcardiographic evaluation allow not only a physically sounder and more transparent approach to the diagnostic assessment of the cardiac electric field than programs based on 12-

lead ECG evaluation, but they may be easily expanded to furnish informative visualization of the underlying physiological events and diagnostic criteria.

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