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Methods of noninvasive electrophysiological heart examination basing on solution of inverse problem of electrocardiography

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Abstract. The article represents the main noninvasive methods of heart electrical activity examination, theoretical bases of solution of electrocardiography inverse problem, application of different methods of heart examination in clinical practice, and generalized achievements in this sphere in global experience.

1. Introduction

This Modern functional diagnostics provides the most variable instrumental methods of examination both invasive and noninvasive. The most widespread and available methods of heart examination is electrocardiography (ECG). In spite of prior use in cardiology it is also successfully used for examination of patients with diseases of lungs, kidneys, liver, endocrine glands, and blood system and also in pediatrics, geriatrics, oncology, sports medicine, etc. Using ECG it is possible to detect heart rate and as a result to identify any heart rhythms disturbances; to detect the disturbances of heart electrical conduction which may lead to decrease of its pumping ability and even to its complete cessation; to detect defects or damages of heart muscle caused by chronic or acute disease.

In spite of availability and informational content under real conditions ECG records are affected by internal and external disturbances which disrupt the given informational fragments and as a result cause additional problems in the process of generation of ECG analysis and interpretation computer systems. Even the solution of supposedly absolutely simple problem of ECG division into separate cardiac cycles (RR intervals) requires using quite difficult detection algorithms of QRS-complexes.

Voltage is significantly influenced by correct recording technique and also the distance from explorative electrode to current source. The size of ECG waves is inversely related to squared distance from electrode to current source. It means that the farther electrode is located from current source the less voltage of electrocardiogram complexes is. Therefore after removal of electrodes more than 12 sm from heart further change of voltage appears to be insignificant.

2. Methods and techniques

Electrocardiographic method also has essential limtations. Activity of definite myocardial subdivisions is insufficiently resembled in electrocardiographic signals recorded in direct leads. The example is the difficulty in ECG diagnosing of myocardial infarction of left ventricular posterobasal subdivisions. Besides according to principle of superposition in electrodynamics electrocardiogram is a sum of electrical potentials occurring from the sources in multiple myocardial points. Since electrophysiological processes in different parts of cardiac muscle run simultaneously it is quite difficult to determine local electrical activity of myocardium using indirect ECG leads. For example human atrial repolarization wave under normal rhythm conditions is not apparent in ECG because it is “covered” by high-amplitude QRS complex resembling ventricular depolarization. The same limitations are also characteristic for the method of vector cardiography [1].

Wider opportunities are peculiar for the method of superficial electrocardiographic mapping of chest. The method involves simultaneous recording of multiple (from 40 to 250 and more) unipolar ECG leads from the surface of chest and construction of maps of electrical potential distribution on the chest surface by means of interpolation for each cardiocycle time interval. However the given method does not provide accurate determination of local electrical myocardial activity. If electrode is located on the surface of chest contributions to ECG signal from the nearest and the most distant relative to recording electrode of myocardium segment have approximately one order difference. For the electrode placed on heart surface this difference equals to three orders. Therefore, methods of invasive ECG recording are used aimed at maximum approach of electrodes to heart surface to determine local electrical activity of heart.

Transesophageal electrophysiological heart examination is based on the introduction of a probe with recording electrodes into the esophageal cavity. Esophagus in a definite region is quite closely adjacent to posterior wall of left atrium and posterior wall of left ventricle that is why intraesophageal ECG-signals selectively record activity of these heart compartments. Intraesophageal electrocardiography is used particularly for differential diagnostics of supraventricular and ventricular arrhythmias. However the given method allows determining local electrical activity of only certain heart structures.

Invasive electrophysiological heart examination based on direct recording of electrogram complexes from epicardial or endocardial heart surfaces is used for complex evaluation of electrophysiological heart processes and topical diagnostics of heart rhythm disturbances. The given methods can be applied to the “open heart” under thoracotomy conditions and also basing on interventional technologies of introduction of recording devices (catheters) into the heart cavities by transvessel access or into pericardium cavity by its transcutaneous puncture under fluoroscopic supervision.

Modern implementations of the given methods provide precise three-dimensional coordinates of recording electrodes by nonfluoroscopic methods and visualization of results in the form of isopotential and isochronic maps on the models of heart compartments by means of computer graphics. Computer models of heart compartments are built basing on multiple points of electrocardiogram recording with the known coordinates and also on the data of computed and magnetic resonance heart tomography.

This group includes methods of noncontact endocardial mapping based on introduction of “floating” balloon catheter into heart cavity, recording of electrocardiogram complex on its surface and reconstruction by calculation method according to received data of endocardial electrograms.

The drawback of the given methods which is overcome in this invention is their invasive character. The analogues of the invention are methods of reconstruction of electrograms in the inner points of the chest by calculating method according to the data of simultaneous recording of ECG complex on the chest surface. The given methods are based on the solution of inverse problem of electrocardiography. Inverse ECG problem mathematically is the task of harmonic extension of potential towards the sources that is Koch’s task for Laplace equation. Calculating region in which Laplace equation is assumed, is the part of the chest limited by the external surface of heart, chest surface on which ECG recording is available and imaginary cross-sections of the chest at the level of diaphragm and clavicles.

On the part of chest surface where ECG recording is available means of electrical potential received as a result of ECG-mapping and also statement of zero equation of normal potential derivative are assumed. These data represent the statement of Koch’s task.

Koch's task involves finding the potential of electrical field in the given region and its trace on heart surface and cross-sections of the chest for the potential in calculating region to satisfy Laplace equation and on the surface of torso where ECG recording is available Koch's statement.

One of the methods of electrocardiography inverse problem solution is the method of reconstruction of electrical field on "quasiepicardium" which is conventional spherical surface surrounding heart. Mathematically the method is based on the presentation of potential of heart electrical field in the form of harmonic polynomial (solid spherical harmonic) ratios of which from statement of equality (or minimum root-mean-square deviation) of means of polynomial and ECG-signal in the points of its recording taking into account zero equation of normal derivative of potential are located on the chest surface. Polynomial of not more than 4 level is used for stabilization of the solution. The method has a significant drawback: reducing sphere radius that is on drawing near the surface of "quasiepicardium" to the real heart surface the accuracy of potential reconstruction abruptly falls. On drawing surface of "quasiepicardium" near the chest surface, resolution of the method in terms of determination of local electrical myocardium activity reduces.

To solve boundary problems for Laplace equation methods of integral equations of potential theory in English-language literature more known as boundary element methods are widely used. The given methods particularly provide the presentation of heart and torso surfaces in the form of polygonal surfaces that is the division of boundary surfaces into multiple triangular elements.

The closest to the represented method (prototype) is the method of Noninvasive Electrocardiographic Mapping (Noninvasive Electrocardiographic Imaging, ECGI) where the superficial mapping is performed using 224 unipolar electrodes placed on a special waistcoat which patients wear during the examination. Surfaces of torso and heart are determined on the basis of computed or MR-tomography of the chest. Algorithm of reconstruction is based on the solution of electrocardiography inverse problem by the method of boundary elements. Heart and torso surfaces are represented in the form of polygonal surfaces. System of matrix-vector equations which is by the way of elementary transformations amounts to simultaneous linear algebraic equations is used for solution of inverse ECG problem. The method was used for determination of localization of accessory conduction pathways in WPW symptomatic syndrome, ectopic sources in ventricular extrasystole and tachycardia, reconstruction of dynamics of myocardial activation in atrial flutter.

A significant drawback of the analyzed method is the use of chest model with fixed factor of specific electrical conduction. Specific electrical conduction of different organs and tissues of the chest significantly differs. Floating factor of electrical conduction of biological tissues significantly influences electrical field of the heart in the chest that is confirmed by the data of experimental examinations. The difference between electrical conduction of lungs and surrounding soft tissues (4-5 times) plays the greatest role. Potentials of cardiac electrical field of model sources calculated for homogenous and inhomogenous models of the chest differ by 15%-20%. Therefore, ignoring of electrical inhomogeneity of the chest tissues leads to large deviations in reconstruction of cardiac electrical field [1]. To solve the inverse ECG problem method of regularization by A.N.Tikhonov [2] is used. It fundamentally includes the following claims:

1. Heart condition determines its electrical activity.
2. The amount, position and choice of heart model points assume maximum resolution for examination of electrical processes taking place in the heart.
3. Heart model points of the patient are elementary heart dipoles each of which in the system of heart coordinates has location, direction and behavior in time of its value, and define electrical activity of a patient.
4. According to electrocardiographic presentation potential value generated by the heart and recorded on the torso of a patient (direct task of electrocardiography) is determined from the formula including the value of electrical potential in j-point of standard lead ($j = 1, \ldots, 12$); average specific electrical resistance of torso and proportionality factor based on the characteristics of electrical activity of the region on the surface of patient's heart model surface [3].

In the developed system for noninvasive supervision of patient's heart state determination of electrical heart activity is performed by means of construction of linear algebraic equation system in which the number of unknowns equals to the number of points of patient's heart model. For this purpose the surface of patient's heart model is "divided" into adjacent Sm noncrossing regions. The number of possible different m regions equals to the number of electrically active i heart points. The given solution of electrocardiography inverse problem allows multifold increasing of accuracy in location of myocardium damages. If in the process of standard electrocardiographic examination it is possible to determine electrical activity of only 8 regions of heart surface then in this approach the determinant is the number of electrically active points in patient's heart model. Such methods of signal processing based on averaging of ECG cycles distortion in phase space of coordinates allow increasing efficiency of assessment of reference cardiac cycle [3].

The solution of electrocardiography inverse problem was firstly introduced already in 70s of the last century (B.Taccardi, R.Barr, R.Plonsey). The first efficient algorithm of electrocardiography inverse problem solution was developed in 1981 by V.V. Shakin. The first clinical tests of noninvasive electrophysiological method based on the solution of ECG inverse problem were performed in1985-87 at Scientific Center of Cardiovascular surgery named after A.N. Bakulev (L.A. Bokeria, V.V. Shakin, G.V. Mirskiy, A.Sh. Revishvili, I.P. Polyakova). Results of clinical tests showed potential perspective of this method, however the level of computing and medical equipment development at that time did not allow its full introducing into clinical practice. For the first time all stages of noninvasive epicardial mapping method was realized by research team headed by prof. W.Rudy (USA) who in 2004 suggested method variant called by the authors as Noninvasive Electrocardiographic Imaging which provides besides superficial ECG mapping computer tomography or MRI of the chest and heart. In 2006 at the premises of tachyarrhythmia surgical treatment department at Scientific Center of Cardiovascular surgery named after A.N. Bakulev under supervision of A.Sh. Revishvili modern software and hardware appliance for noninvasive electrophysiological heart examination was developed; it was based on the solution of electrocardiography inverse problem. Calculative noninvasive activation mapping included several stages:

1. Performance of multichannel electrocardiogram recording from the chest surface in 80 or 240 unipolar leads using different systems of superficial ECG-mapping.
2. Patients with already placed superficial electrodes underwent helical computed tomography of the chest with intravenous contrast. Different helices pitch distance was used: 5-7mm for the whole chest scanning and 3 mm helices pitch distance for heart region scanning.
3. Computed tomography data determined the boundaries of the chest surfaces, epicardial and endocardial heart surfaces, and helped to build realistic tree-D voxel models of torso and heart [4].

Such projects are also very important due to development of interventional and surgical methods of heart rhythm disturbances treatment. For example noninvasive activation heart mapping allows performing electrophysiological and topical diagnostics of heart rhythm disturbances with accuracy which was earlier achieved only on the basis of direct electrocardiographic measurements on the myocardial surface under conditions of surgical intervention [2].

The main advantages of the method are:

- noninvasive character;
- simultaneous mapping of all four heart chambers;
- simultaneous mapping on endocardium and epicardium of heart;
- mapping for one cardiac cycle;
- mapping of arrhythmias characterized by aperiodical electrophysiological processes.
- The main spheres of use of noninvasive activated mapping:
- preoperative diagnostics of hard disturbances of cardiac rhythm before surgical or interventional treatment;
- postoperative supervision, diagnostics of recurrent and incisional arrhythmias after surgical or interventional treatment;

- electrophysiological and topical diagnostics of rhythm disturbances characterized by aperiodical or rarely recurrent electrophysiological processes;
- electrophysiological heart examination in patients having contraindications for heart catheterization.
- cardiac resynchronizing therapy.

Noninvasive activation mapping performed during preoperative period reduces the time of invasive electrophysiological examination, duration of surgical intervention and intraoperational fluoroscopy, and significantly reduces absorbed radiation doses for a patient and medical staff.

During postoperative period noninvasive activation mapping provides an opportunity to control the efficiency of performed catheter ablation without repeated invasive interventions, to determine recurrences of rhythm disturbances in proper time and to determine topical characteristic and electrophysiological nature of incisional.

The opportunity of mapping of all four heart chambers per one cardiac cycle allows performing detailed diagnostics of cardiac arrhythmias having unstable character or nonperiodic course of electrophysiological processes. This group involves up to 30% of all rhythm disturbances: from rare actopic extrasystole to atrial fibrillation. Simultaneous mapping on epicardium and endocardium allows determining the depth of the source of pathologic myocardium excitation relative to epicardium and endocardium. This information is important for the choice of tactics of surgical (interventional) treatment of Wolff–Parkinson–White (WPW) and ectopic arrhythmias [2].

Thus progress in this sphere goes on. Over the last years effective algorithms of electrocardiography inverse problems solution were created [5-7] and all necessary technical means have been already widely use in clinical practice for a long time (Computed tomography and electrocardiotopography with multichannel ECG recording on the body surface). The development of special hardware and software appliances for electrophysiological heart examination based on solution of electrocardiography inverse problems goes on. Many tens of computer electrocardiographic databases with hundreds and thousands of well annotated ECG in standard, orthogonal and other low-channel leads and also large libraries of intracardiac electrograms were created. Many of them are essentially computer implementations of atlases which are predecessors of databases. Some databases such as for example “The Common Standards for Electrocardiography (CSE) Database” [7] and “The Physikalisch-Technische Bundesanstalt (PTB) Diagnostic ECG Database” played significant part in development of modern computed electrocardiography. All algorithms of ECG preprocessing, filtration isoline, cardiocycle marking, automatic diagnostics, etc.; which now are involved in electrocardiograph software were developed and verified with the help of this databases [8, 9].

Databases of tree-D medical images resulted from the use of tomographic of other intrascopy methods were created and are actively developed. For example as part of “The Cardiac Atlas Project (CAP)” big database containing results of noninvasive intrascopic examinations of normal and pathological hearts aimed at clinical research and educational purposes was created and is constantly extended.

However there are no databases containing all necessaries elements for verifications and improvement of methods and algorithms applied for solution of electrocardiography inverse problem. In internet it is possible to find only certain cases containing simultaneously multichannel ECG measured on the chest surface and new medical description of torso and heart shape.

Synchronized base combining data of simultaneously performed electrophysiological and tomographic clinical investigations could become foundation for improvement of methods and algorithms used for solution of inverse electrocardiographic problem and for their detailed experimental check. Moreover such database would be also useful for solution of a variety of other problems restricting development of noninvasive electrocardiotopography. At many scientific centers intensive complex examinations of heart activity mechanisms are held among them: modeling of structural and functional relations at different levels (biomolecules, myocytes, myocardial tissues, the whole heart and the whole body) and modeling of electrophysiological, mechanical and biophysical processes (metabolism and blood circulation). The important and useful result of this work is program

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packages with open code for multiscale modeling of electrophysiological processes such as SCIRun, CHASTE (Cancer, Heart and Soft Tissue Environment) and CARP (Cardiac Arrhythmia Research Package).

At the clinic several different systems of electroanatomic mapping which allow performing mapping of activation process on endocardium with the help of catheters are used. In the process of simultaneous mapping (recording) of electrical potential on the body surface and potential reconstruction on the heart surface there is an opportunity to compare received results with real measurement.

The first verification method of location of initial myocardial activation area is comparison of results of inverse electrocardiographic problem solution with data received in the process of invasive catheter operations, search and elimination of ectopic excitation sources. The search of octopic sources suggests direct measuring of electrical potentials on epicardium during open heart operations or endocardium in the process of invasive catheter electoanatomic heart examination. In addition to the above before operative treatment noninvasive electrocardiotopographic examination is performed (multielectrode superficial electrocardiogram is recorded) and also tomography (CT or MRI) for detailed description of torsoanatomy and accurate position of superficial electrodes is performed. These data are necessary for solution of inverse electrocardiological problem and determination of wave excitation code. After performing the operation of ectopic source removal coordinates of identified ectopic excitation sources are compared with the results of restoration of excitation wave front pathway received while solving inverse problem [8].

The second verification method is simultaneous performance of electrocardiotopographic examination (records of superficial electrocardiograms) and stimulation (cardiac stimulation by method of periodic electric stimulation of certain points of excitable myocardium with the help of cardiostimulatar electrodes or using special active catheter electrode in the process of invasive catheter electroanatomical examination). Accurate position of stimulating electrodes in the heart is registered with the help of tomographic examination (in case of permanent cardio stimulator use) or in the process of invasive catheter electroanatomical heart examination as for example using CARTO XP [8].

3. Conclusion

Based on the above to solve a direct problem (calculation of potential on the body surface according to set parameters of electrical generator) and inverse problem (noninvasive reconstruction of heart electrical field according to ECG on the body surface) the following data are needed:

- Simultaneously recorded electrocardiosignals in multiple points on the chest surface
- Synchronized with electrocardiosignals numeric tree-D model of the chest and internal organs of a patient
- Position of points on the chest surface in which electrodes were located
- Synchronized with electrocardiosignals numeric tree-D model of the heart and its internal chambers
- Data about electrical conduction of internal organs, myocardium and endocavitary blood
- Parameters of myocardium biophysical model as excitation environment
- Position of stimulation points and electrical stimulation parameters

Therefore numeral solution of electrocardiography inverse problem with anatomical accuracy providing possibility of faultless surgical intervention is complex task including development, improvement and providing with necessary speed of algorithms operation at all stages: starting with voxel models of density distribution of tissues resulted from CT or MRI, localization of electrodes on the body surface to visualization of physiological processes in myocardium and formation of reasonable diagnostic conclusion.

A big number of noninvasive mapping systems such as ИРМ-7100 of FUKUDA DENSHI company (Japan) and CARDIAC -112.2 system 2PA company (Czech Republic) has recently appeared abroad. These systems are designed in the form of permanently installed appliances with the patient connected to them by means of many wires. In addition there is an insistent necessity to study the patient's organism in different types of activity and also while physical exercises. Taken into account these circumstances nowadays diagnostic multichannel electrocardiographic systems with telemetry connection channel are being developed.

In general informational content and as a result diagnostic value of above mentioned methods is different and significance of each of them is relative. Nevertheless analyzed approaches to development of informational technologies of ECG processing for solution of the problem of dangerous heart diseases determination allow performing timely diagnostics and providing appropriate treatment.

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