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Inverse Problem of Electro- and Magnetocardiography: Review and Recent Progress

O. Dössel

Institute of Biomedical Engineering, University of Karlsruhe, Karlsruhe, Germany

Correspondence: *od@ibt.etec.uni-karlsruhe.de*

Abstract. More than 20 years of research in imaging of bioelectric sources in the human heart have passed and a lot of effort has been devoted to the topic. In spite of that the method is not established in clinical practice but still just an interesting research topic of enthusiastic scientist. A review together with a comprehensive literature survey is given in this article. Recent developments and new trends are outlined.

Keywords: *Inverse Problem, Electrocardiography, Magnetocardiography, Bioelectric Sources*

Introduction

Under the headline of the "inverse problem of electro- and magnetocardiography" all attempts are summarized to find detailed information about the location and distribution of the bioelectric sources in the heart from the electric potentials at the body surface (Body Surface Potential Maps BSPM) or the magnetic fields (MCG) outside the body. Different compromises between what is possible to reconstruct on the one hand and what makes sense for the cardiologists on the other hand have been suggested: from single dipole localizations to activation maps. In any case it is the objective to support the cardiologist during diagnosis and therapy of many different diseases of the heart: from arrhythmias to myocardial infarction. A breakthrough of the method will be guaranteed if the "added value" for the physician justifies the additional effort (investment and time). Several review articles have been published lately by famous scientists working in the field [96, 284, 319, 325]. The intention of this work is to give a complete literature survey and to highlight some new trends.

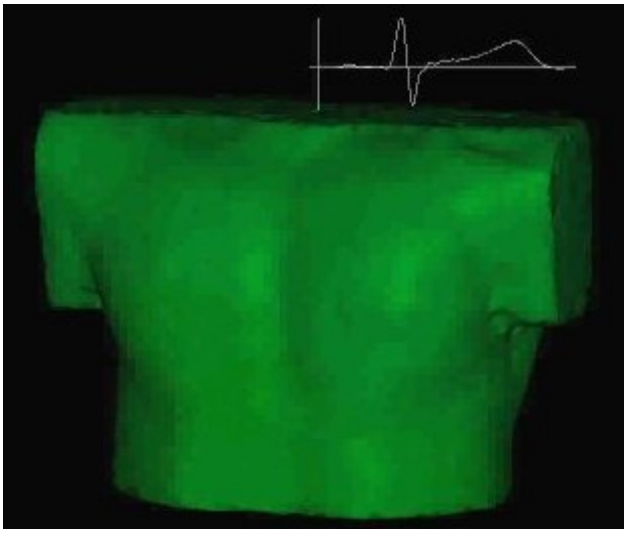
Methods

Source Models

The following list shows all source models that are discussed in the literature up to now:

- Moving Dipole / Equivalent Current Dipole ECD [88, 91, 196, 215, 276, 374]
- Multiple Dipoles [80, 89]
- Multipole Expansions [90, 192, 395]
- Epicardial Potentials [23, 78, 105, 166, 231, 234, 237, 335, 398]
- Endocardial Potentials [221, 231]
- Current Density Distributions [51, 54, 97, 217, 362]
  (Current Density Estimates CDE)
- Average-Intensity and Wiener Reconstruction of Current Distribution [48]
- Activity Maps/Activation Isochrones
  - based on Uniform Double Layer (UDL) [103, 104, 197, 221, 277, 280, 306, 313, 397]
  - based on relative extrema [109]
- Transmembrane Potential Distributions [54]

If there is apriori information available supporting the assumption of a single localized source the moving dipole is obviously the best choice. Epicardial and endocardial potentials can be compared to measured data using electrode-socks (epicardial) or intraventricular electrodes (endocardial electrodes, baskets, balloons, see part IX Evaluation). Activity maps are in line with the way electrograms are typically interpreted by cardiologists in the catheter laboratory but they can be misleading if the Uniform Double Layer assumption is not valid e. g. in case of infarction.



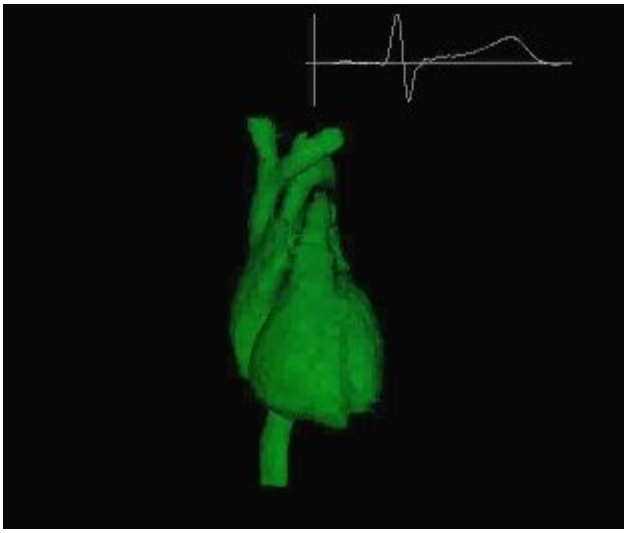


Figure 1. BSPM and reconstructed epicardial potentials using Tikhonov O. Order regularization [138].

The reconstruction of the transmembrane potential as the driving force of all bioelectric phenomena can be easily compared to computer models of the spread of depolarization in the heart, but a straight forward evaluation with measured data is not possible.

The localization of one or more current dipoles is an optimization task and both Levenberg-Marquard and Simplex algorithms have been used. A critical issue is to what extent the solution depends on the initial values.

The reconstruction of epicardial and endocardial potentials and of current density estimates is a linear problem with fast solvers. Time consuming in this case is the use of advanced regularization techniques (see part V Regularization Techniques). The other inverse problems are non-linear and demand for iterative solvers that are often time consuming as well.

In computer simulations and in phantom experiments all source models work fine. The preference to the various models must come from the cardiologist: he/she has to judge on the diagnostic value of the results and it can be expected that different diseases ask for different models.

Volume Conductors

The solution of the inverse problem demands for a computer model of the volume conductor. Various models have been used or proposed:

- spheres or cylinders [183, 223, 229, 374]
- homogeneous torso models [275]
  (individual outer body shape, inside just one conductivity)
- inhomogeneous torso models [37, 50, 100, 171, 196, 199, 237, 279, 289, 301, 351]
  (e. g. based on MR-data, segmentation and conductivities of all tissue classes)
- anisotropic torso models [30, 84, 121, 176, 182, 348]
  (e. g. anisotropic conductivity of heart or skeletal muscle)
- dynamic torso models
  (considering the movement of the heart)

Meanwhile it is generally accepted that spheres, cylinders and also homogeneous torso models are not an adequate choice: The "added value" of the imaging method as compared to 12-lead ECG concerning localization accuracy or specificity of diagnosis is too small.

The inhomogeneous torso model is used in most of the studies today. It is a "hot topic"

whether the anisotropy of the conductivity of the muscle has to be taken into account or not. Computer simulations show a significant effect on the BSPM [121]. On the other hand patient studies e. g. about the localization accuracy of current dipoles show promising results even though anisotropy is neglected. The determination of fiber orientation in individual patients[160] seems to be too laborious. But digital image processing can be used to match a model heart (including fiber orientation) on to an individual heart [139] thus bringing anisotropic individual torso models within reach.

The movement of the heart has been neglected up to now. This is reasonable if the signals during the QRS-peak are reconstructed onto an enddiastolic torso model. As soon as reconstructions are carried out during T-wave the errors are expected to be large if not a systolic torso model is used in that case.

Numerical Field Calculation

Since we are dealing with the quasi-static situation all techniques that have been invented for that case have already been used:

- BEM: Boundary Element Method [9, 54, 56, 57, 222, 267, 277, 278, 295]
- FEM: Finite Element Method [78, 131, 252, 396, 398]
- FDM: Finite Difference Method [35, 121]
- FVM: Finite Volume Method [389]

BEM is not practical in case of anisotropic conductivities. So if anisotropic tissue properties proove to be essential only FEM and FDM can be used (FVM is more or less a dialect of FDM). The same is true if conductivity gradients inside one tissue should become important (see e. g. the variations of conductivity inside the skull).

Sometimes some basic restrictions of all numerical field calculation techniques have not been considered properly: near to a source a very fine discretization is needed (or higher order shape functions). For example if in BEM a dipole is located some millimeter near to a boundary, which is very typical for dipoles in the heart, in this area the size of the triangles describing the boundary has to be in the millimeter range. Otherwise the result might have large errors.

Regularization Techniques

The inverse problem of electro- and magnetocardiography is ill-posed meaning that small measurement errors can lead to very large artifacts in the reconstructed image. A regularization technique is needed to come to a stable solution. Sometimes the moving dipole model, the multiple dipole approach and the multipole expansion are also called "regularization techniques" since they stabilize a solution by using specific model assumptions. A more interesting problem is to find the best regularization technique in the other "real imaging methods" given in part 'Source Models'.

The basic equation for the forward problem is

$$L \cdot \vec{x} = \vec{b}$$

with L: lead field matrix

$\vec{x}$: unknown source term

$\vec{b}$: measured signals

If the minimum-norm-solution (Tikhonov zero-order) is looked for

$$\hat{\vec{x}} = \min\left\{\left\|L \cdot \hat{\vec{x}} - \vec{b}\right\|^2 + \gamma\left\|\hat{\vec{x}}\right\|^2\right\}$$

the solution is easily given by:

$$\hat{\vec{x}} = L^T\left(LL^T + \gamma \cdot I\right)^{-1} \cdot \vec{b}$$

A generalization of this approach is:

$$\hat{\vec{x}} = \min\left\{\left\|W \cdot \left(L \cdot \hat{\vec{x}} - \vec{b}\right)\right\|_2^2 + \gamma\left\|B \cdot \hat{\vec{x}} - \vec{d}\right\|_p^p\right\}$$

This way we allow for

- a weighting matrix W to compensate for different SNRs of various sensors [392]
- a weighting matrix B for depth normalization and/or a mollifier matrix B like the Laplacian Laplacian D (see LORETTA) [391]
- an apriori solution d that attracts the reconstructed solution (see Twomey) [399]
- other norms for the regularization term (p=1, p=2, p=infty)

The following approaches have been tested:

- Spatial techniques
  - Tikhonov 0. and 2. Order [54, 102, 222, 252, 277]
  - adaptive local regularization [324]
  - Twomey[399]
- maximum entropy/expectation/likelihood [49]
- temporal techniques
  - activation maps based on UDL [20, 104, 197, 277, 280]
  - activation maps based on relative extrema [109]
- spatio-temporal techniques [228, 231, 308]
- multiple constraints [299, 330]
- admissible solution approach [321, 332]

If Tikhonov regularization methods are used with different assumptions of the norm (L1, L2, L_∞), every choice demands for a specific depth-normalization - otherwise the solution will have a bias in the depth direction [390].

Every regularization leads to a spatial filtering of the solution: the imaging system behaves like a spatial low-pass filter [125]. This is typical for any imaging system (compare e. g. with the Modulation Transfer Function MTF). Unfortunately in our case the smallest wavelength (that is the highest spatial frequency) that can be detected is in the range of 10 mm. Many authors try hard to push the lowest detectable wavelength down e. g. to 8 mm by taking the risk that large artifacts might show up in the images.

The right choice of the regularization parameter also is a critical issue. The L-curve method [400] is used quite often. Also the Zero-Crossing-Method [95] and the CRESO-Method [18] have been proposed.

Since computer models of the heart become more and more realistic and can describe not only the healthy heart but also various diseases the question should be raised whether these models can be used in order to stabilize a solution [13, 19, 22, 52, 83, 97, 99, 126, 148, 259, 349, 363, 401, 402]. The Twomey method is looking for a solution "near to a template". This approach has to be expanded to the spatio-temporal domain since the computer models of the heart deliver a complete time course of the signals (ECG/MCG). This could lead finally to a

"hypothesis test" for detailed diagnosis of diseases of the heart.

Electrode- and Magnetometer Arrangements

A couple of arrangements for electrodes [69, 241, 320] and magnetometers [43, 44, 219] have been proposed. In a previous work we have optimized the electrode arrangement of BSPM with respect to the imaging of epicardial potentials [124, 125]. The result can be easily understood using the sampling theorem: In areas with high spatial frequencies in the BSPM (that is right above the apex) the electrodes must be placed very dense (e. g. 10 mm distance) whereas in areas with low spatial frequencies the electrodes can be very sparse (e. g. 100 mm distance). A similar result comes out for MCG. Typical arrangements for MCG are far away from the optimum due to the restricted possibilities of dewar-constructions.

Electrodes measuring the Laplacian [172, 223, 227, 282, 294, 370] are claimed to be of advantage. Since the information is clearly linear-dependent to the information gained with conventional arrangements the only advantage could be a better signal-to-noise-ratio with respect to the source vector. This has not been demonstrated yet.

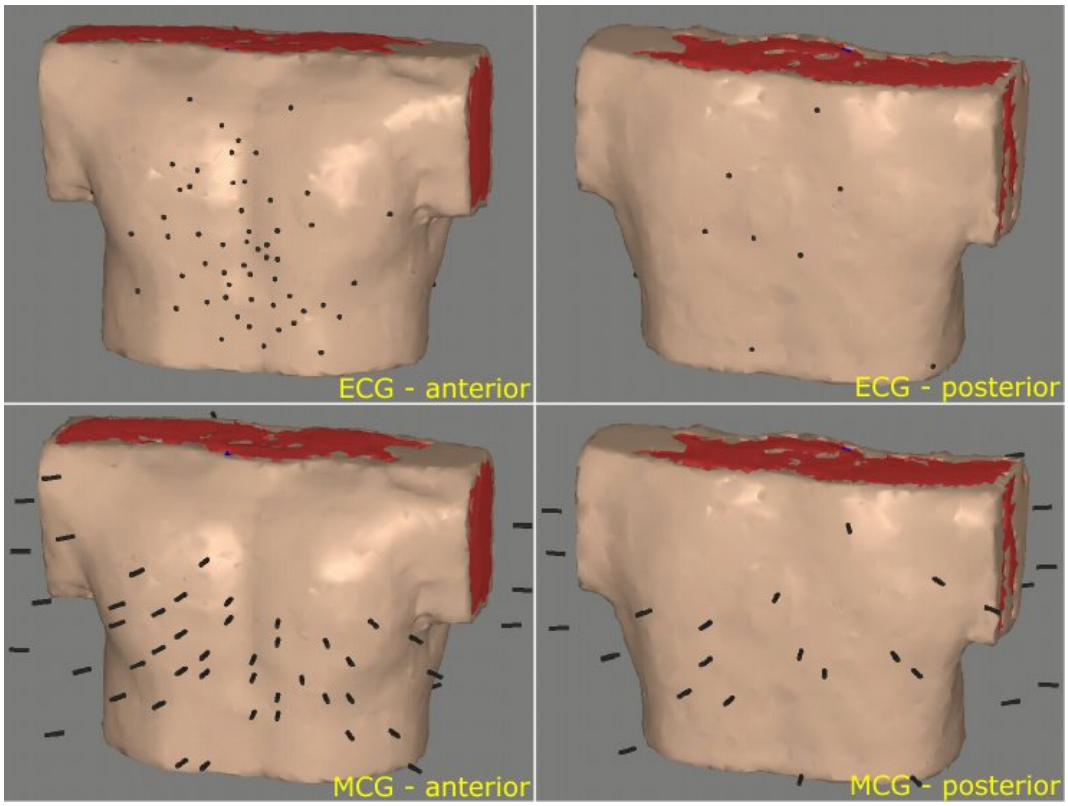


Figure 2. Optimized electrode- and magnetometer arrangements [124, 125]

Artifacts

In medical imaging we distinguish between contrast, blurring (leading to a bad MTF) and artifacts (e. g. false hot spots).

Concerning the inverse problem of electro- and magnetocardiography noise in the measured data leads to blurred images (spatial low pass filtering) if the regularization parameter is chosen properly.

Measurement errors and especially errors in the model of the volume conductor can lead to

artifacts: the dipole is localized in a wrong position or the epicardial potentials show maxima at wrong locations. This is a very critical issue for a medical imaging technique. It shows up that the geometry and tissue conductivity of the areas near to the sources (the heart) and near to the electrodes has to be modeled very carefully [184]. This can be easily understood with the lead-field theory and the reciprocity theorem [32].

ECG/MCG-competition

For many years the question is raised again and again: what is better, ECG or MCG? A couple of items have to be investigated more thoroughly before the answer can be given:

- The signal-to-noise ratios of typical ECG and MCG signals have to be compared. If one method delivers better SNRs under realistic circumstances it has a clear advantage.
- The localization error for current dipoles and the probability of image artifacts due to model errors has to be compared for ECG and MCG [9, 184, 189, 236, 257, 258, 297, 350]
- The content of "silent sources" for ECG and MCG in typical source patterns has to be investigated [337, 360, 367]. The question has to be adressed whether ECG and MCG deliver lineary independent information about the sources or not.

The simultaneous use of BSPM and MCG data will obviously be the best choice for research centers that investigate new methods.

Evaluations

A lot of work has been devoted to the evaluation of the localization power of ECG and/or MCG concerning single current dipoles. The following type of studies have been carried out:

- computer simulations [54, 57, 232, 321, 352, 353]
- phantom experiments [1, 8, 140, 189]
- animal experiments [167, 335, 342]
- patient studies [2, 88, 185, 312, 314]

An accuracy of 2 mm to 10 mm was achieved and MCG localizations have proven to be a little bit better than ECG localizations.

Also some imaging techniques have been evaluated lately. The following techniques to measure epicardial or endocardial electric potentials have been used:

- electrode socks around the heart [78, 335, 342]
- single endocardial electrodes that can be localized [3, 238, 378]
- basket electrodes [222]
- balloon electrodes [222, 339, 403, 404]

Some results are promising others are a little bit disappointing [197]. This is obviously extremely interesting "work in progress".

Applications

The following applications of the method have been proposed and investigated:

- accessory paths (e. g. Wolf-Parkinson-White-Syndrome) [28, 92, 112, 115, 206, 207, 213, 263, 271]
- branch block [27]
- atrial flutter/fibrillation [204]
- ventricular flutter/fibrillation [4, 272, 274, 354]
- ectopic beats [24, 88, 167, 266, 358]

- ischemia[25, 261, 314, 317, 333]
- infarctions
- risk for ventricular tachycardia [6, 11, 26, 113, 201, 203, 205, 260, 269, 270, 272, 273]
- viability studies [12]
- fetal heart diagnosis [302, 305, 375, 377]

Many of the diseases can be treated using RF-ablation or surgery if the right location for the electrode or the cut is known. BSPM and MCG promise to cut down the cath-lab time for patient and physician from several hours to a couple of minutes.

Conclusions

It seems as if fast and simple methods (e. g. simple volume conductor models) have not proven to deliver enough "added value" to the physicians. Models and algorithms become more sophisticated. The same time computers become faster and cheaper so that also complicated procedures for data analysis can become practical in clinical everyday life. So there is still a chance that imaging of bioelectric sources will become an important clinical method in future. More emphasis has to be put on evaluation to convice the physicians about the opportunities of the method.

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