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(71) **Applicant**: **NORTHEASTERN UNIVERSITY** [US/US]; 360 Huntington Ave., 900RP, Boston, MA 02115 (US).

(72) **Inventors**: **COLL-FONT, Jaume**; 21 Creighton St., Apt. 3, Jamaica Plain, MA 02130 (US). **BROOKS, Dana, H.**; 5 Hinckley Rd., Milton, MA 02186 (US).

(74) **Agents**: **GORDON, Dana, M.** et al.; FOLEY HOAG LLP, Seaport West, 155 Seaport Blvd., Boston, MA 02210-2600 (US).

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(54) **Title**: DETERMINING GEOMETRIC CHANGES, ROTATIONS, AND/OR TRANSLATIONS OF THE HEART BASED ON ELECTROCARDIOGRAM MEASUREMENTS

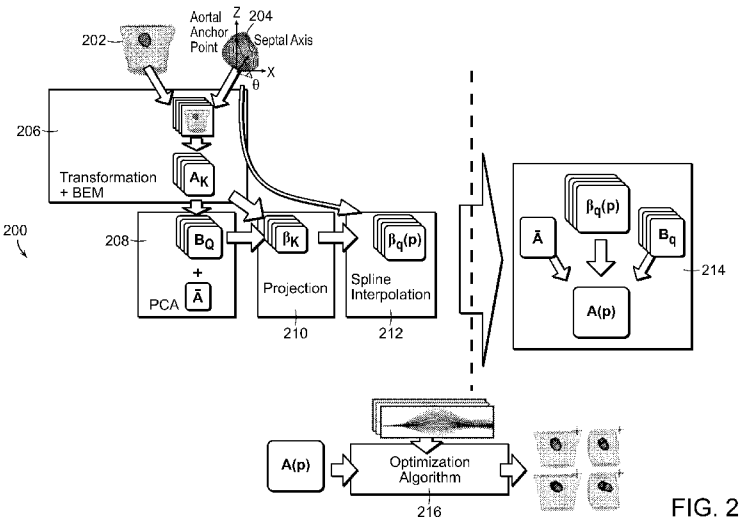


FIG. 2

(57) **Abstract**: Computer-implemented methods and system are disclosed for determining geometric changes, rotations, and/or translations of the heart of a patient based on ECG measurements.

DETERMINING GEOMETRIC CHANGES, ROTATIONS, AND/OR TRANSLATIONS OF THE HEART BASED ON ELECTROCARDIOGRAM MEASUREMENTS

RELATED APPLICATION

This application claims the benefit of priority to U.S. Provisional Patent Application No. 62/210,783 entitled PHYSIOLOGICALLY INFORMED MODEL FOR CORRECTION IN FORWARD MODELS IN ECGI, which was filed on August 27, 2015 and is incorporated by reference herein.

BACKGROUND

Solutions to the inverse problem of electrocardiography, also known as Electrocardiographic Imaging (ECGI), non-invasively image the electrical activity of the heart to localize and quantify normal and abnormal cardiac electrophysiology, and have recently attracted considerable attention in the research community. These methods have great promise to aid planning of catheter ablation procedures to treat already diagnosed cardiac abnormalities as well as for screening and diagnosis of patients with possible undiagnosed, or not fully diagnosed, abnormalities. They solve a mathematical problem that uses electrocardiogram (ECG) measurements on or inside the body surface to characterize the unknown electrical activity of the heart. The heart's electrical activity can be described with a variety of "source models" based on electrical potentials or currents on or inside the heart. Solving this mathematical problem relies on the calculation of a "forward" model relating the potentials or currents on or inside of the heart at a given time instant t, (x_t), with the ECGs (y_t); this forward model is summarized in a "forward matrix" (here, noted by A).

$$y_t = Ax_t$$

However, ECGI has some limitations that impede its application in routine clinical practice. One of them is the ill-posedness of the forward model, which causes inverse solutions to be unreliable even with small levels of noise in the inputs and of errors in the forward model. In particular, errors in the forward model introduce "noise" that is usually ignored and which is particularly pervasive when solving the inverse problem. One source of error in the forward models is created by changes in shape, position, and/or orientation of the heart within the torso, which are not considered in the static geometry used to calculate

the forward model. It is thus desired to adapt the forward model to the continuous changes that the underlying geometry undergoes during the measurement of the ECGs.

Moreover, the capacity to track the geometric changes within the body based on the ECG measurements would be beneficial to interventions that require registration of the position of the heart within a fixed coordinate system such as during ablation procedures using an intracardiac catheter. It would be particularly helpful to accomplish this determination of intrathoracic geometry based on the measurements made for ECGI itself.

SUMMARY OF THE DISCLOSURE

In accordance with one or more embodiments, a computer-implemented method is disclosed for determining geometric changes, rotations, and/or translations of the heart of a patient based on ECG measurements. The method includes the steps of:

(a) receiving a computational volume model of at least the heart and torso of the patient, including an assignment of conductivities of components of the computational volume model and an identification of the locations of ECG measurement electrodes positioned on the torso surface;

(b) identifying one or more geometric changes, rotations, and/or translations of the heart, which can include a sequence or continuous set of such changes, rotations, and/or translations, during a period of ECG measurements;

(c) computationally applying a selected set of the one or more geometric changes, rotations and/or translations from step (b) to the computational volume model from step (a) multiple times to generate multiple modified computational volume models, and developing a forward model for each one of the modified computational volume models;

(d) generating a function based on the forward models generated in step (c) to approximate any forward model based on any geometric changes, rotations, and/or translations identified in step (b);

(e) receiving measured electrical potentials on or in the heart of a patient and the corresponding ECG electrical potentials measured on the torso surface of the patient for one or more heartbeats; and

(f) estimating one or more geometric changes, rotations, and/or translations of the heart during ECG electrical potential measurements from step (e) by making the function in step (d) best relate the measured electrical potentials on or in the heart of a patient and the corresponding ECG electrical potentials measured on the torso surface of the patient, both obtained in step (e).

A computer-implemented method of determining geometric changes, rotations, and/or translations of the heart of a patient based on ECG measurements in accordance with one or more further embodiments includes the steps of:

(a) receiving a computational volume model of at least the heart and torso of the patient, including an assignment of conductivities of components of the computational volume model and an identification of the locations of ECG measurement electrodes positioned on the torso surface;

(b) identifying one or more geometric changes, rotations, and/or translations of the heart, which can include a sequence or continuous set of such changes, rotations, and/or translations, during a period of ECG measurements;

(c) computationally applying a selected set of the one or more geometric changes, rotations and/or translations from step (b) to the computational volume model from step (a) multiple times to generate multiple modified computational volume models, and developing a forward model for each one of the modified computational volume models;

(d) generating a function based on the forward models generated in step (c) to approximate any forward model based on any geometric changes, rotations, and/or translations identified in step (b);

(e) receiving ECG electrical potentials measured on the torso surface of the patient for one or more heartbeats;

(f) estimating the electrical potentials on or in the heart of the patient with an independent algorithm using the ECG electrical potentials measured on the torso surface of the patient from step (e) and the function generated in step (d) evaluated with an initial estimate of one or more geometric changes, rotations, and/or translations;

(g) estimating one or more geometric changes, rotations, and/or translations of the heart during ECG electrical potential measurements by making the function generated in step (d) best relate the electrical potentials on or in the heart of a patient estimated in step (f) and the corresponding ECG electrical potentials measured on the torso surface of the patient obtained in step (e); and

(h) iteratively repeating steps (f) and (g) using the one or more geometric changes, rotations, and/or translations obtained in step (g) in place of the initial estimated one or more geometric changes, rotations, and/or translations until desired convergence criteria are met.

A computer system in accordance with one or more embodiments comprises at least one processor, memory associated with the at least one processor, and a display, and a program supported in the memory. The program determines geometric changes, rotations, and/or translations of the heart of a patient based on electrocardiogram (ECG) measurements. The program contains a plurality of instructions which, when executed by the at least one processor, cause the at least one processor to:

(a) receive a computational volume model of at least the heart and torso of the patient, including an assignment of conductivities of components of the computational volume model and an identification of the locations of ECG measurement electrodes positioned on the torso surface;

(b) identify one or more geometric changes, rotations, and/or translations of the heart, which can include a sequence or continuous set of such changes, rotations, and/or translations, during a period of ECG measurements;

(c) computationally apply a selected set of the one or more geometric changes, rotations and/or translations from step (b) to the computational volume model from step (a) multiple times to generate multiple modified computational volume models, and developing a forward model for each one of the modified computational volume models;

(d) generate a function based on the forward models generated in step (c) to approximate any forward model based on any geometric changes, rotations, and/or translations identified in step (b);

(e) receive measured electrical potentials on or in the heart of a patient and the corresponding ECG electrical potentials measured on the torso surface of the patient for one or more heartbeats; and

(f) estimate one or more geometric changes, rotations, and/or translations of the heart during ECG electrical potential measurements from step (e) by making the function in step (d) best relate the measured electrical potentials on or in the heart of a patient and the corresponding ECG electrical potentials measured on the torso surface of the patient obtained in step (e).

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a simplified flowchart illustrating an exemplary process in accordance with one or more embodiments for estimating transformations of a heart based on ECG measurements.

FIG. 2 is a simplified flow diagram illustrating an exemplary process in accordance with one or more embodiments for estimating transformations of the heart based on ECG measurements.

FIGS. 3 and 4 are diagrams illustrating the results of applying techniques in accordance with one or more embodiments to localize the position of an exemplary canine heart placed within a tank filled with a conducting medium.

FIGS. 5 and 6 are diagrams illustrating the application of techniques in accordance with one or more embodiments to a synthetic experiment where the heart moves within the torso following a respiration-like trajectory.

FIG. 7 is a simplified block diagram illustrating an exemplary computer system, on which computer programs in accordance with one or more embodiments may operate as a set of computer instructions.

DETAILED DESCRIPTION

Various embodiments disclosed herein relate to computer-implemented methods and systems that use the relation between position and shape of a patient's heart and the electrical measurements on or inside of the patient's body to estimate a transformation of a nominal discretized geometry of the heart within the torso. The function is first estimated and then used to estimate the geometric transformations from the electrical measurements.

The computer-implemented methods and systems in accordance with various embodiments first generate a function to approximate forward matrices for unknown heart geometries that could be generated by applying geometry changes, rotations and/or translations to a nominal heart geometry. The methods and systems then use this function to find the geometric transformations that best relate the electrical activity on or inside of the heart with electrical measurements on or inside of the body (ECGs).

FIG. 1 is a simplified flowchart 100 generally illustrating an exemplary process in accordance with one or more embodiments for estimating transformations of an original discretized geometry of the heart within the torso during ECG measurements.

To generate the function to approximate forward matrices, a nominal geometry of the body describing, at least, the heart and torso geometries (but that can include other organs and internal structures and voids) is received along with the corresponding conductivities at step 102.

Then the geometric changes, rotations, and/or translations of the heart are determined at step 104. These geometry transformations can be generated synthetically or from previous imaging of those transformations using MRI, CT or ultrasound. In one or more embodiments, these geometry transformations include translation and rotation of the heart.

Other embodiments can include geometry transformations that model the contraction movements of the heart or any other parameterized transformation of the heart geometry.

Next at step 106, the geometry transformation is applied to the nominal geometry at a number of degrees of transformation. For example, if translation of the heart is

considered, multiple transformed geometries will be generated by moving the heart at different locations within the torso.

For each transformed geometry, a forward model is computed using a solver of the forward problem in electrocardiography. These forward models form representative samples in the space of possible forward models obtained after the transformations of the geometry. In accordance with one or more embodiments, a surface potential is used to model the electrical sources of the heart and the forward problem is solved with a boundary element method (BEM). In other embodiments, alternate source models can be used such as monopoles or dipoles distributed on the heart surface or within its 3D volume, and also alternate forward solvers such as finite element method (FEM), finite difference (FDM), finite volume, method of fundamental solutions (MFS), etc.

These sample forward models are then used with an interpolation method to generate a smooth function that approximates the forward matrices that would be obtained after transforming the heart geometry with the determined geometry transformation at step 108.

In accordance with one or more embodiments, a two-step interpolation is used that combines a linear and a non-linear part. The final form of the interpolation scheme is:

$$\hat{A}(p) = \sum_{q=1}^{Q} \widehat{\beta_q}(p) B_q + \bar{A},$$

where $\bar{A}$ is the mean forward matrix, B_q are a set of Q basis matrices, for some integer Q, and $\widehat{\beta_q}(p)$ is a set of Q non-linear functions, mapping from the transformation parameters describing the geometry transformations to the real numbers $\widehat{\boldsymbol{\beta}_q}(\boldsymbol{p}): \Xi \rightarrow \mathbb{R}$

According to this embodiment, $\bar{A}$ is computed as the average forward matrix of the sample forward matrices generated; the basis matrices B_q are computed as the first Q principal components using the decomposition of principal component analysis (PCA) applied to the sample forward matrices.

According to this embodiment, the non-linear functions $\widehat{\beta_q}(p)$ are generated through interpolation using a multi-dimensional spline. This spline interpolation is applied to the projections of the sample forward matrices onto the basis matrix B_q and uses the transformation parameters describing the geometry transformation as its domain.

To find the geometric transformation that best relates the electrical activity on or inside of the heart with electrical measurements on or inside of the body at step 112, recordings of the electrical activity of the heart inside or outside of the body for one or a sequence of heartbeats are received at step 110.

A function to assess the similarity between the electrical measurements and the synthesized using the approximate forward model and an estimate of the electrical activity of the heart is defined.

In accordance with one or more embodiments, the least squares metric is used and an individual geometry transformation per each heartbeat b is assumed:

$$\min_{p_b} \sum_{b=1}^{B} \sum_{t=1}^{T} \left\| y_{t,b} - \hat{A}(p_b)\hat{x}_t \right\|_2^2,$$

In alternate embodiments, a continuous transformation of the geometry in time is used:

$$\min_{p_t} \sum_{t=1}^{T} \left\| y_t - \hat{A}(p_t)\hat{x}_t \right\|_2^2,$$

Alternate embodiments include the use of different metrics to assess similarity and/or the incorporation of prior knowledge, including physiological and pathophysiological knowledge, in the form of additional constraints or additional terms in the similarity function.

We provide an initial estimate of the transformation parameters that describes the degree of geometric transformation. This initial estimation can be calculated using prior knowledge or with the aid of structural imaging systems such as ultrasound or impedance imaging. Then in one or more embodiments, the electrical activity of the heart is estimated using an ad-hoc ECGI method using the approximated forward matrix ($\hat{A}(p)$) and the measured ECGs. The estimated electrical activity on or inside of the heart is then used in conjunction with the approximated forward matrix to synthesize an estimation of the measured ECGs. If the synthesized and measured ECGs do not match sufficiently, the transformation parameters are then adjusted with the aid of an optimization algorithm. This two-step procedure is iteratively repeated until the convergence criteria are satisfied.

In accordance with one or more embodiments, the truncated singular value decomposition (TSVD) is used to estimate the electrical potentials on or inside of the heart surface.

In other embodiments, other ECGI methods, such as Tikhonov regularization, Tikhonov regularization with additional constraints or activation-based methods, can be used.

Other embodiments can incorporate prior knowledge, including physiological or pathophysiological knowledge, and/or direct electrical measurements of the electrical activity of the heart into the ECGI method.

FIG. 2 is a simplified flow diagram 200 generally illustrating an exemplary process in accordance with one or more embodiments for estimating transformations of an original discretized geometry of the heart within the torso based on ECG measurements. The nominal geometry 202 is provided to the algorithm and the geometric transformations 204 are determined to be translations and rotations of the heart. The nominal geometry is then transformed a number of times to provide sample forward matrices 206. The sample forward matrices are then introduced in a PCA algorithm 208 to compute the basis matrices and the mean forward matrix. Then, the sample forward matrices are projected onto the basis matrices 210 to obtain the sample projected coefficients. These sample projected coefficients are then introduced into a spline interpolation method 212 to obtain the non-linear function $\widehat{\beta_q}(p)$. The basis matrices, mean forward matrix and non-linear functions are then combined to generate the function approximating forward matrices 214.

Once generated the function approximating forward matrices, it is introduced into the optimization algorithm 216 with the measured electrical potentials on or inside of the body. This optimization results in the transformation parameters that best relate the estimation of the electrical measurements and the estimation of the electrical activity of the heart.

Example 1:

FIGS. 3 and 4 show the results of applying a process in accordance with one or more embodiments to localize the position of an exemplary canine heart placed within a tank filled with a conducting medium.

The nominal geometry of the experiment consists of a closed discretized surface mesh comprising 337 nodes surrounding the epicardial surface of the canine heart and another mesh comprising 284 nodes representing the outer surface of the tank enclosing it. During the experiment, the heart is paced at various locations in the ventricles and electrical recordings are taken on both the heart, with 247 electrodes, and tank surfaces, with 192 electrodes. The heart and torso geometries are generated such that each measurement electrode corresponds to an individual node. The heart sources are modeled as the potential distribution along the surface around the heart and the sample forward matrices are computed using BEM.

The process described in the diagram of FIG 2 is used. Here, we reconstruct a static translation and rotation of the heart for each heartbeat, using the added knowledge of the measured heart and tank surface potentials. No information about the actual transformations of the heart is used in the algorithm however. After convergence of the optimization algorithm, the geometry is then transformed in accordance to the results provided by the process. Then a new forward matrix is computed using the BEM software. A comparison between measured tank surface potentials, synthesized using the nominal geometry and the transformed geometries is shown in FIG 3. The synthesized potentials using the transformed geometry are more similar to the measured potentials than the synthesized using the nominal geometry. FIG 4 shows the transformed geometry of the heart 401 overlaid over the nominal geometry 402 for two different heartbeats. This figure shows how the process is capable of finding a position of the heart that best relates the potentials on the heart and tank surfaces. FIGS. 3 and 4, illustrate how the process is capable of improving the forward models through transformation of the geometry.

Example 2:

FIGS. 5 and 6 illustrate the application of a process in accordance with one or more embodiments to a synthetic experiment where the heart moves within the torso following a respiration movement and when no measurement of the electrical activity on the heart is available. The nominal geometry used in this experiment is the same as in Example 1, but the movements of the heart are now synthesized to emulate the respiration movement. Thus, after moving the heart at a number of locations following a respiration process, the corresponding forward matrices are computed and the body surface potentials are synthesized using a sequence of measured heart surface potentials. Then, noise is added to

the synthesized body surface potentials to emulate a realistic signal to measurement noise ratio of 30dB. The nominal geometry and the said synthesized body surface potentials are then used to recover the position of the heart within the torso for all heartbeats. To increase verisimilitude, a different forward model is used in this step than the one used to synthesize all the body surface potentials, thus mimicking unavoidable modeling errors that will be encountered in a realistic setting. The implementation of the invention is as described in the diagram of FIG 2 and uses the TSVD inverse of all combined heartbeats to reconstruct the electrical potentials on the heart. FIG. 5 shows the comparison between the true body surface potentials (left column) and the synthesized using the nominal geometry (middle column) and synthesized using the transformed geometries (right column). The transformations of the geometry obtained with this invention are capable of better describing the true body surface potentials. FIG. 6 shows the estimated position of the heart 601 overlaid on top of the nominal position 602 for different phases within the respiration cycle. This figure shows how the process is capable of accurately finding the true position of the heart moving due to respiration. This example illustrates how the process is capable of accurately reconstructing the heart geometry when only electrical measurements on the body surface are available.

The methods, operations, modules, and systems described herein may be implemented in one or more computer programs executing on a programmable computer system. FIG. 7 is a simplified block diagram illustrating an exemplary computer system 10, on which the computer programs may operate as a set of computer instructions. The computer system 10 includes at least one computer processor 12, system memory 14 (including a random access memory and a read-only memory) readable by the processor 12. The computer system also includes a mass storage device 16 (e.g., a hard disk drive, a solid-state storage device, an optical disk device, etc.). The computer processor 12 is capable of processing instructions stored in the system memory or mass storage device. The computer system additionally includes input/output devices 18, 20 (e.g., a display, keyboard, pointer device, etc.), a graphics module 22 for generating graphical objects, and a communication module or network interface 24, which manages communication with other devices via telecommunications and other networks 26.

Each computer program can be a set of instructions or program code in a code module resident in the random access memory of the computer system. Until required by

the computer system, the set of instructions may be stored in the mass storage device or on another computer system and downloaded via the Internet or other network.

Having thus described several illustrative embodiments, it is to be appreciated that various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to form a part of this disclosure, and are intended to be within the spirit and scope of this disclosure. While some examples presented herein involve specific combinations of functions or structural elements, it should be understood that those functions and elements may be combined in other ways according to the present disclosure to accomplish the same or different objectives. In particular, acts, elements, and features discussed in connection with one embodiment are not intended to be excluded from similar or other roles in other embodiments.

Additionally, elements and components described herein may be further divided into additional components or joined together to form fewer components for performing the same functions. For example, the computer system may comprise one or more physical machines, or virtual machines running on one or more physical machines. In addition, the computer system may comprise a cluster of computers or numerous distributed computers that are connected by the Internet or another network, and may include various forms of specialized hardware for purposes of computational acceleration.

Accordingly, the foregoing description and attached drawings are by way of example only, and are not intended to be limiting.

CLAIMS

We claim:

1. A computer-implemented method of determining geometric changes, rotations, and/or translations of the heart of a patient based on electrocardiogram (ECG) measurements, the method comprising the steps of:

(a) receiving a computational volume model of at least the heart and torso of the patient, including an assignment of conductivities of components of the computational volume model and an identification of the locations of ECG measurement electrodes positioned on the torso surface;

(b) identifying one or more geometric changes, rotations, and/or translations of the heart of interest during a period of ECG measurements;

(c) computationally applying a selected set of the one or more geometric changes, rotations and/or translations from step (b) to the computational volume model from step (a) multiple times to generate multiple modified computational volume models, and developing a forward model for each one of the modified computational volume models;

(d) generating a function based on the forward models generated in step (c) to approximate any forward model based on any geometric changes, rotations, and/or translations identified in step (b);

(e) receiving measured electrical potentials on or in the heart of a patient and the corresponding ECG electrical potentials measured on the torso surface of the patient for one or more heartbeats; and

(f) estimating one or more geometric changes, rotations, and/or translations of the heart during ECG electrical potential measurements from step (e) by making the function in step (d) best relate the measured electrical potentials on or in the heart of a patient and the corresponding ECG electrical potentials measured on the torso surface of the patient obtained in step (e).

2. The method of claim 1, further comprising:

(g) determining one or more forward models that relate electrical potentials on or in the heart of the patient with corresponding electrical potentials measured on the torso surface of the patient based on the one or more geometric changes, rotations, and/or translations of the heart determined in step (f).

3. The method of claim 2, wherein step (g) comprises applying the one or more geometric changes, rotations and/or translations from step (f) to the computational volume model from step (a) to generate multiple modified computational volume models, and developing a forward model for each one of the modified computational volume models.

4. The method of claim 2, further comprising:

(h) registering the position of the heart with respect to a fixed coordinate system by:

(1) applying the geometric changes, rotations and/or translations from step (g) to the computational volume model from step (a) to generate a modified computational volume model; and

(2) registering the modified computational volume model to the fixed coordinates provided by a navigator system.

5. The method of claim 1, wherein the geometric change comprises a contraction of the heart.

6. The method of claim 1, wherein the geometric changes, rotations, and/or translations of the heart occur continuously during the ECG measurements,

7. The method of claim 1, wherein the geometric changes, rotations, and/or translations of the heart occur over multiple heartbeats during the ECG measurements.

8. The method of claim 1, wherein the one or more geometric changes, rotations, and/or translations of the heart comprise a sequence or continuous set of such changes, rotations, and/or translations of the heart.

9. A computer-implemented method of determining geometric changes, rotations, and/or translations of the heart of a patient based on electrocardiogram (ECG) measurements, the method comprising the steps of:

(a) receiving a computational volume model of at least the heart and torso of the patient, including an assignment of conductivities of components of the computational volume model and an identification of the locations of ECG measurement electrodes positioned on the torso surface;

(b) identifying one or more geometric changes, rotations, and/or translations of the heart of interest during a period of ECG measurements;

(c) computationally applying a selected set of the one or more geometric changes, rotations and/or translations from step (b) to the computational volume model from step (a) multiple times to generate multiple modified computational volume models, and developing a forward model for each one of the modified computational volume models;

(d) generating a function based on the forward models generated in step (c) to approximate any forward model based on any geometric changes, rotations, and/or translations identified in step (b);

(e) receiving ECG electrical potentials measured on the torso surface of the patient for one or more heartbeats;

(f) estimating the electrical potentials on or in the heart of the patient with an independent algorithm using the ECG electrical potentials measured on the torso surface of the patient from step (e) and the function generated in step (d) evaluated with an initial estimate of one or more geometric changes, rotations, and/or translations;

(g) estimating one or more geometric changes, rotations, and/or translations of the heart during ECG electrical potential measurements by making the function generated in step (d) best relate the electrical potentials on or in the heart of a patient estimated in step (f) and the corresponding ECG electrical potentials measured on the torso surface of the patient obtained in step (e); and

(h) iteratively repeating steps (f) and (g) using the one or more geometric changes, rotations, and/or translations obtained in step (g) in place of the initial estimated one or more geometric changes, rotations, and/or translations until desired convergence criteria are met.

10. The method of claim 9, further comprising:

(i) determining one or more forward models that relate electrical potentials on or in the heart of a patient with corresponding electrical potentials measured on the torso surface of the patient based on the one or more geometric changes, rotations, and/or translations of the heart determined in step (h).

11. The method of claim 10, wherein step (i) comprises applying the one or more geometric changes, rotations and/or translations from step (h) to the computational volume model from step (a) to generate multiple modified computational volume models, and developing a forward model for each one of the modified computational volume models.

12. The method of claim 10, further comprising:

(j) registering the position of the heart with respect to a fixed coordinate system by:

(1) applying the geometric changes, rotations and/or translations from step (h) to the computational volume model from step (a) to generate a modified computational volume model; and

(2) registering the modified computational volume model to the fixed coordinates provided by a navigator system.

13. The method of claim 9, wherein the geometric change comprises a contraction of the heart.

14. The method of claim 9, wherein the geometric changes, rotations, and/or translations of the heart occur continuously during the ECG measurements.

15. The method of claim 9, wherein the geometric changes, rotations, and/or translations of the heart occur over multiple heartbeats during the ECG measurements,

16. The method of claim 9, wherein the one or more geometric changes, rotations, and/or translations of the heart comprise a sequence or continuous set of such changes, rotations, and/or translations of the heart.

17. A computer system, comprising:

at least one processor;

memory associated with the at least one processor;

a display; and

a program supported in the memory for determining geometric changes, rotations, and/or translations of the heart of a patient based on electrocardiogram (ECG) measurements, the program containing a plurality of instructions which, when executed by the at least one processor, cause the at least one processor to:

(a) receive a computational volume model of at least the heart and torso of the patient, including an assignment of conductivities of components of the computational volume model and an identification of the locations of ECG measurement electrodes positioned on the torso surface;

(b) identify one or more geometric changes, rotations, and/or translations of the heart of interest during a period of ECG measurements;

(c) computationally apply a selected set of the one or more geometric changes, rotations and/or translations from step (b) to the computational volume model from step (a) multiple times to generate multiple modified computational volume models, and developing a forward model for each one of the modified computational volume models;

(d) generate a function based on the forward models generated in step (c) to approximate any forward model based on any geometric changes, rotations, and/or translations identified in step (b);

(e) receive measured electrical potentials on or in the heart of a patient and the corresponding ECG electrical potentials measured on the torso surface of the patient for one or more heartbeats; and

(f) estimate one or more geometric changes, rotations, and/or translations of the heart during ECG electrical potential measurements from step (e) by making the function in step (d) best relate the measured electrical potentials on or in the heart of a patient and the corresponding ECG electrical potentials measured on the torso surface of the patient obtained in step (e).

18. The system of claim 17, wherein the one or more geometric changes, rotations, and/or translations of the heart comprise a sequence or continuous set of such changes, rotations, and/or translations of the heart.

19. The system of claim 17, wherein the program further includes instructions to:

(g) determine one or more forward models that relate electrical potentials on or in the heart of the patient with corresponding electrical potentials measured on the torso surface of the patient based on the one or more geometric changes, rotations, and/or translations of the heart determined in step (f).

20. The system of claim 19, wherein the program further includes instructions to:

(h) register the position of the heart with respect to a fixed coordinate system by:

(1) applying the geometric changes, rotations and/or translations from step (g) to the computational volume model from step (a) to generate a modified computational volume model; and

(2) registering the modified computational volume model to the fixed coordinates provided by a navigator system.

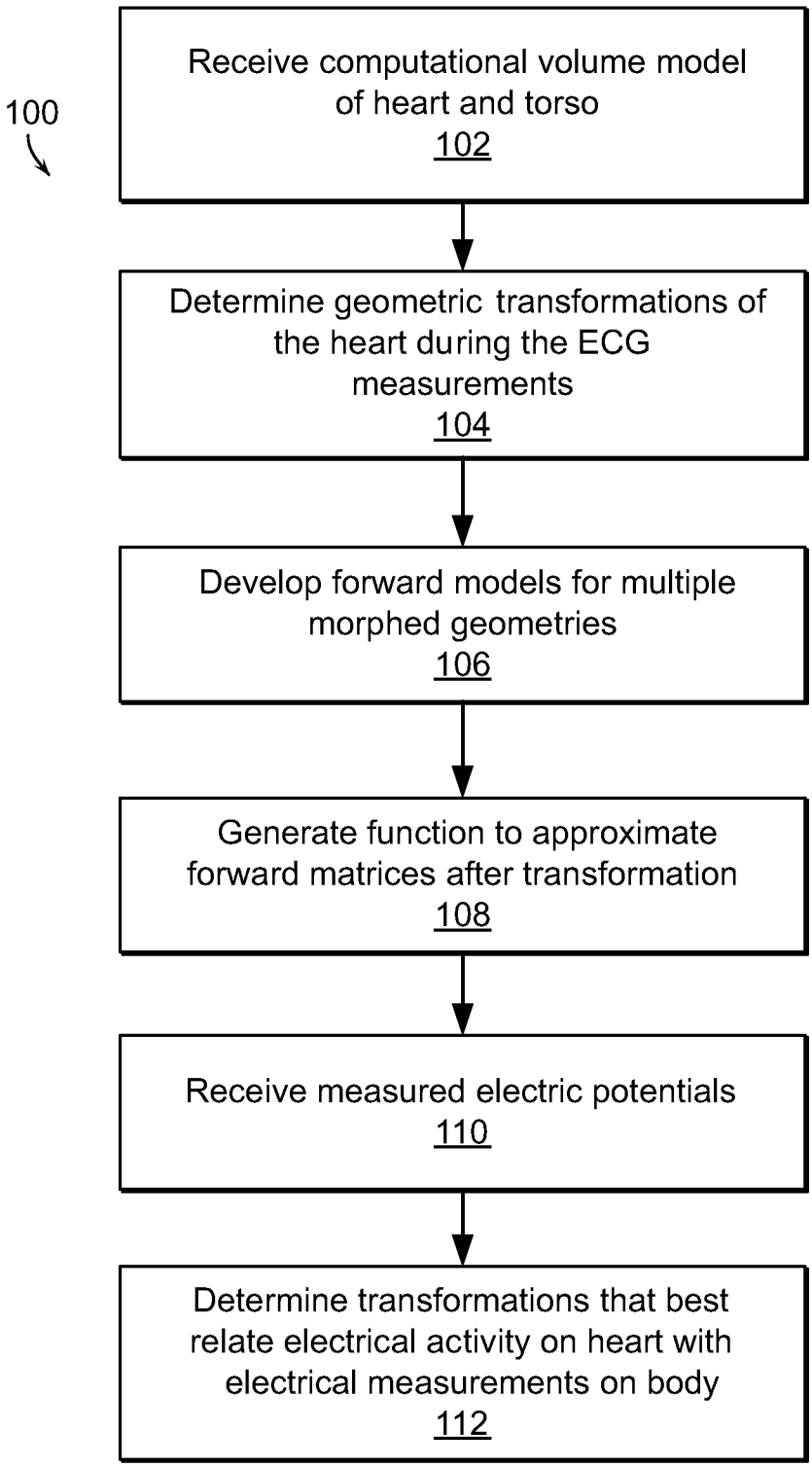

100
Receive computational volume model of heart and torso
102
Determine geometric transformations of the heart during the ECG measurements
104
Develop forward models for multiple morphed geometries
106
Generate function to approximate forward matrices after transformation
108
Receive measured electric potentials
110
Determine transformations that best relate electrical activity on heart with electrical measurements on body
112

FIG. 1

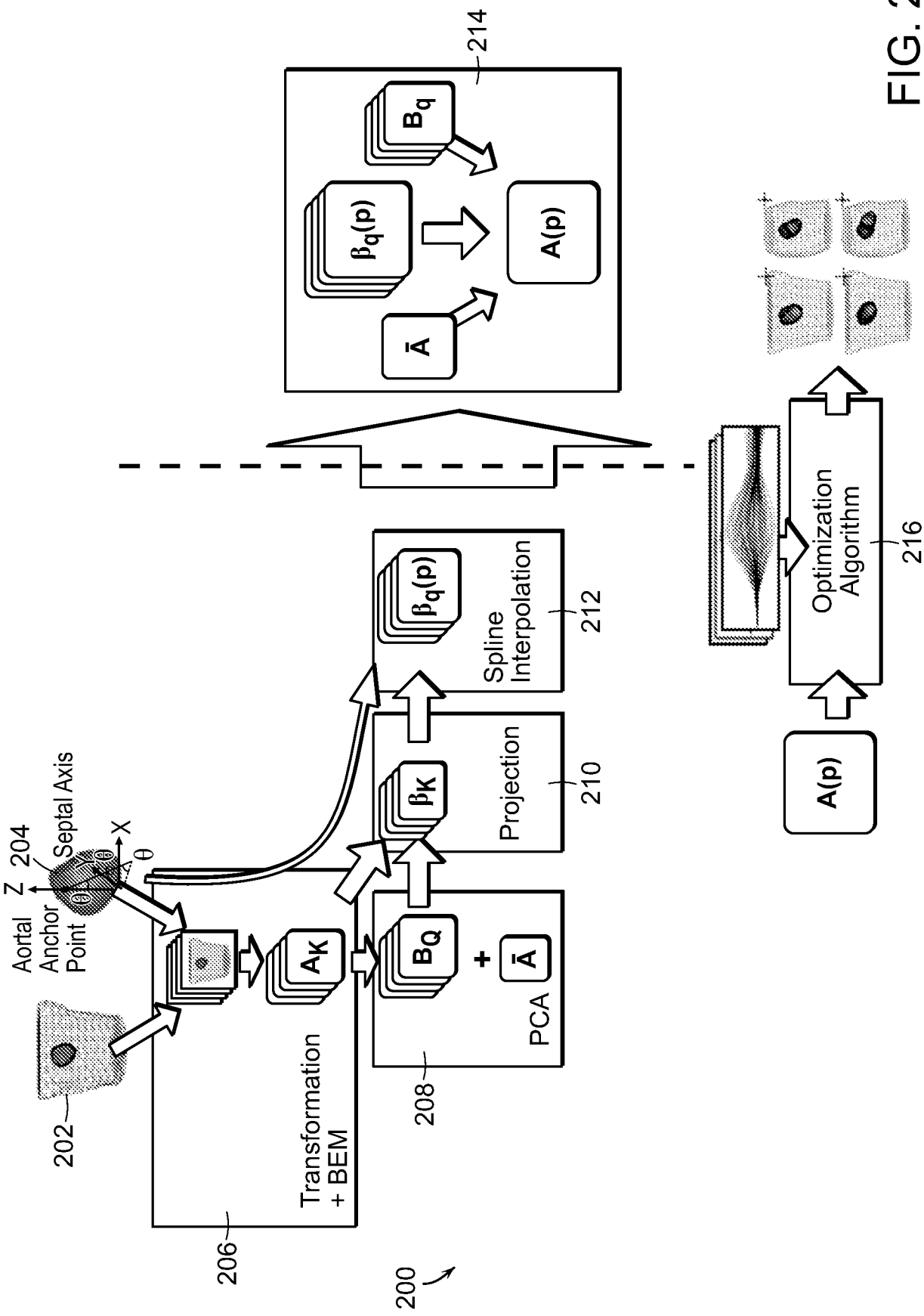

200
202
204
206
208
210
212
214
216
Aortal Anchor Point
Septal Axis
Z
X
θ
Transformation + BEM
PCA
Projection
Spline Interpolation
Optimization Algorithm
A(p)
$\bar{A}$
B_Q
A_K
β_K
$\beta_q(p)$
B_q

FIG. 2

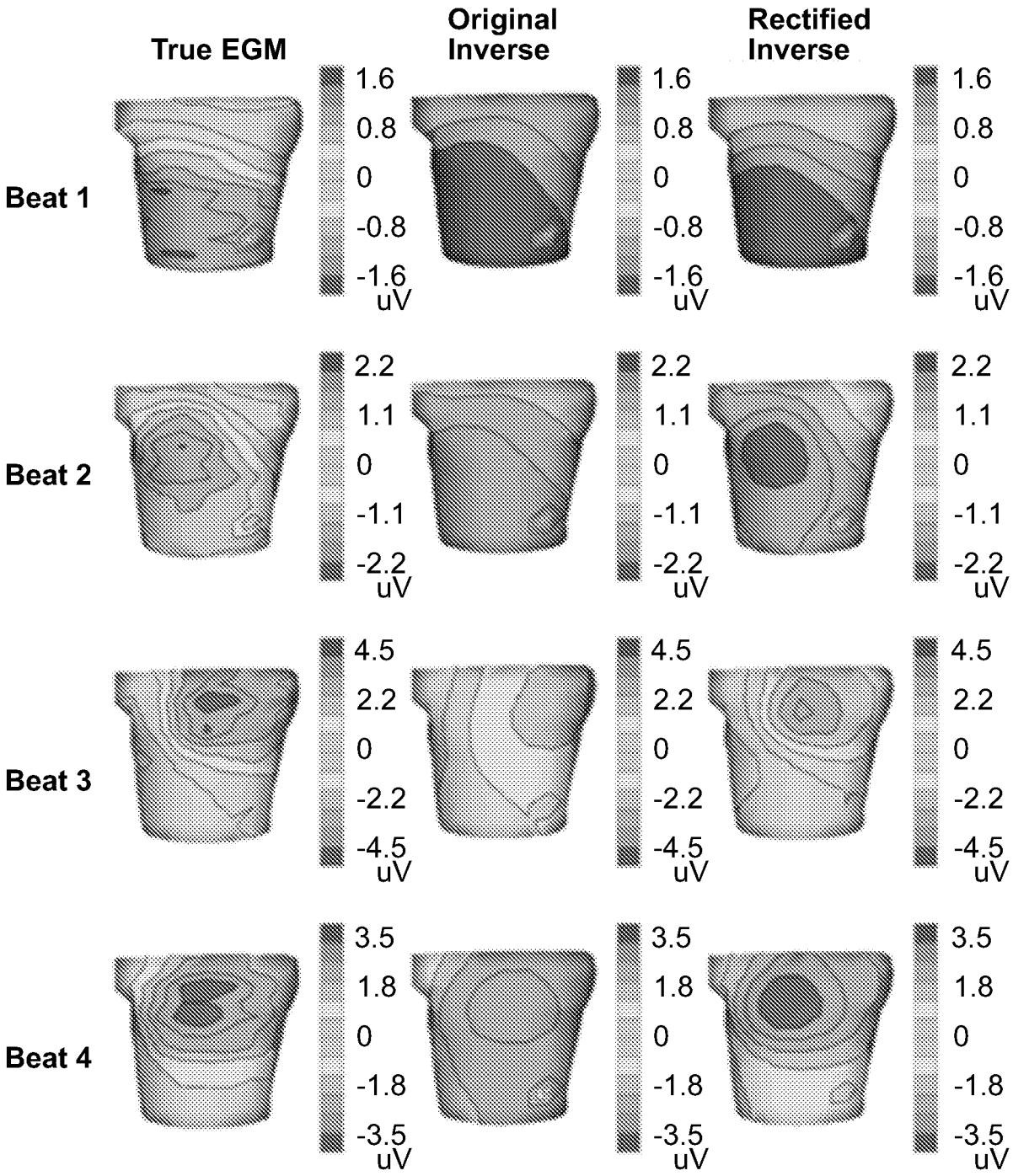

True EGM
Original Inverse
Rectified Inverse
Beat 1
Beat 2
Beat 3
Beat 4
1.6
0.8
0
-0.8
-1.6
uV
2.2
1.1
0
-1.1
-2.2
uV
4.5
2.2
0
-2.2
-4.5
uV
3.5
1.8
0
-1.8
-3.5
uV

FIG. 3

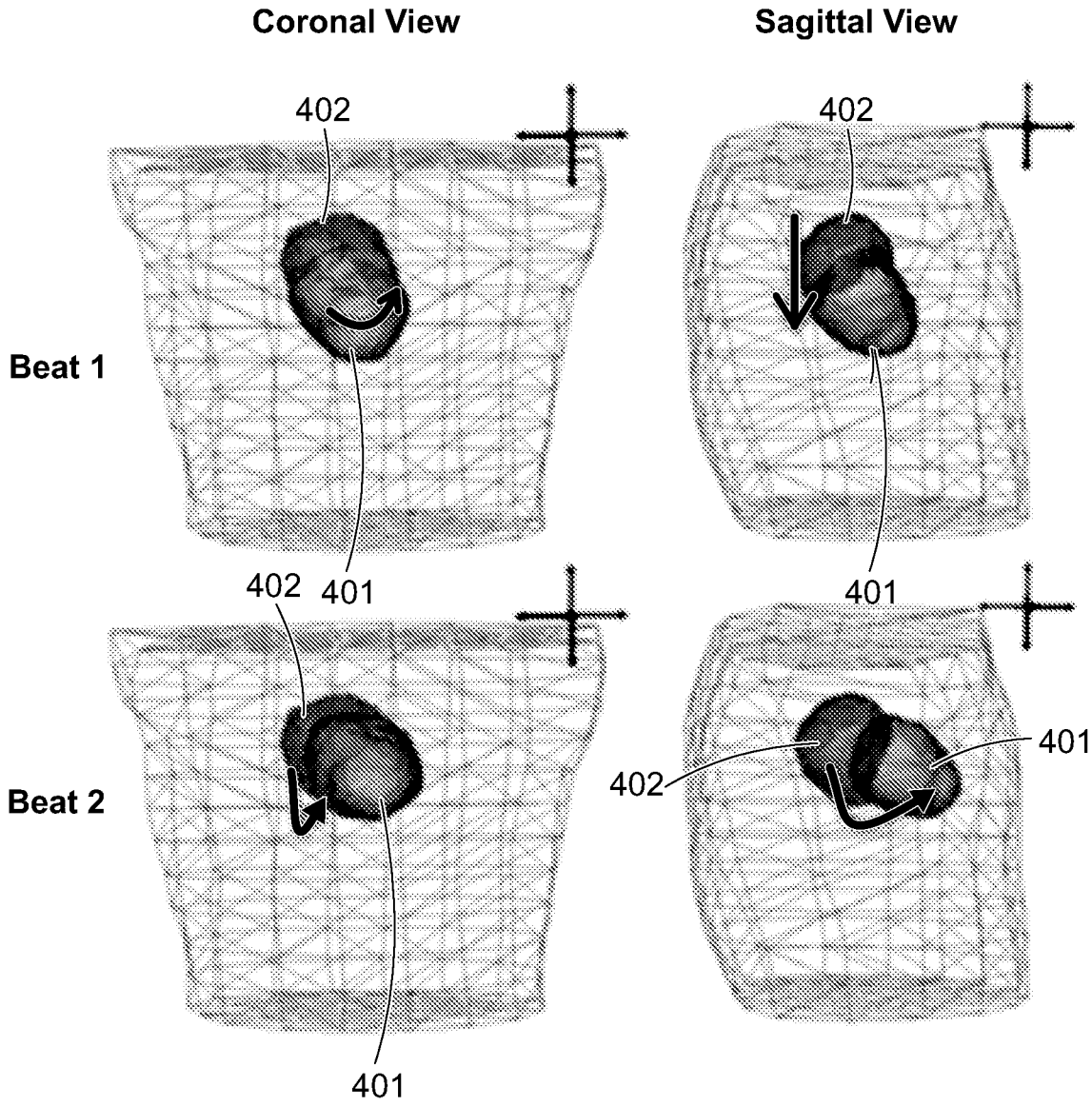

Coronal View
Sagittal View
Beat 1
Beat 2
402
401
402
401
402
401
402
401

FIG. 4

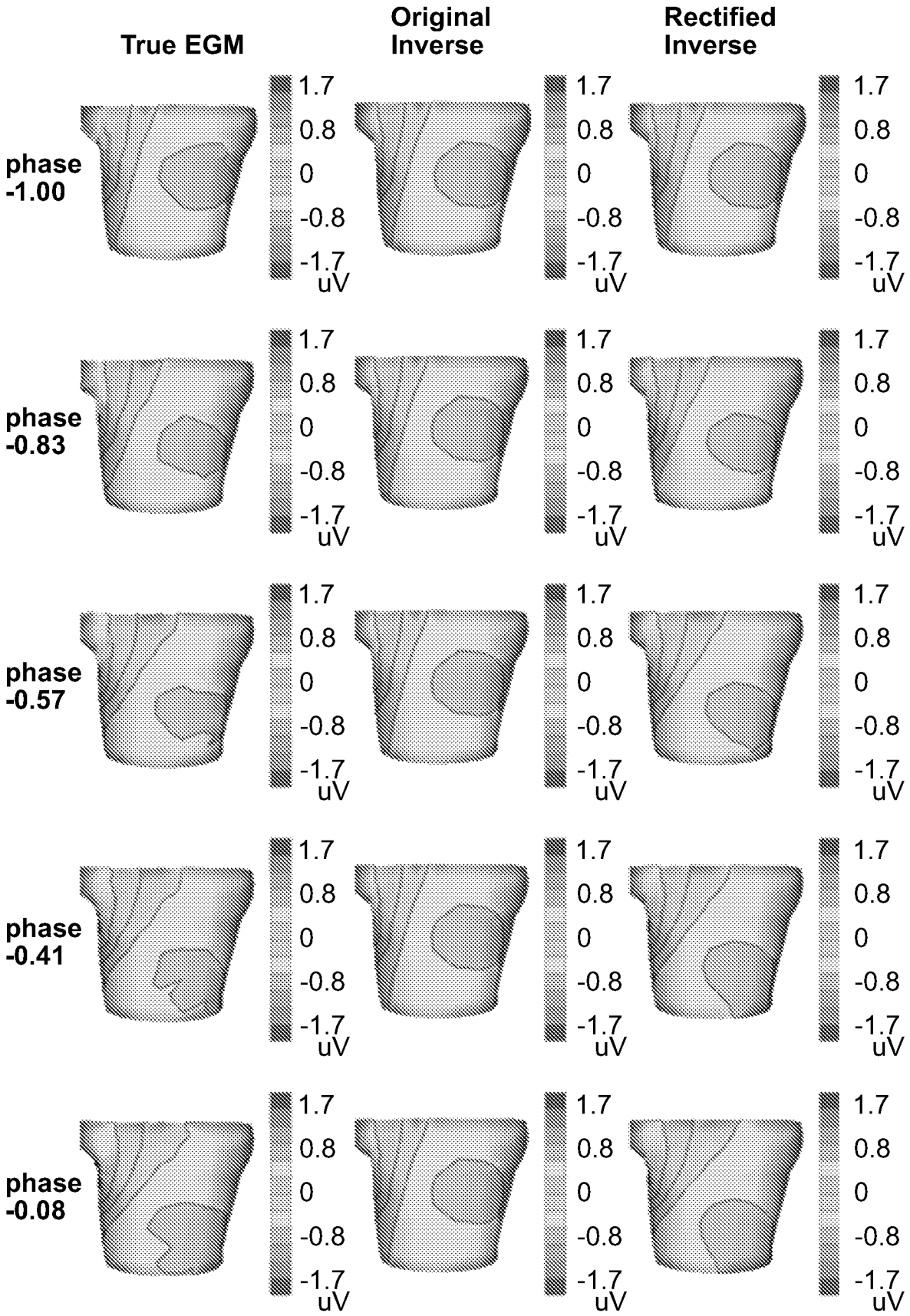

True EGM
Original Inverse
Rectified Inverse
phase -1.00
phase -0.83
phase -0.57
phase -0.41
phase -0.08
1.7
0.8
0
-0.8
-1.7
uV

FIG. 5

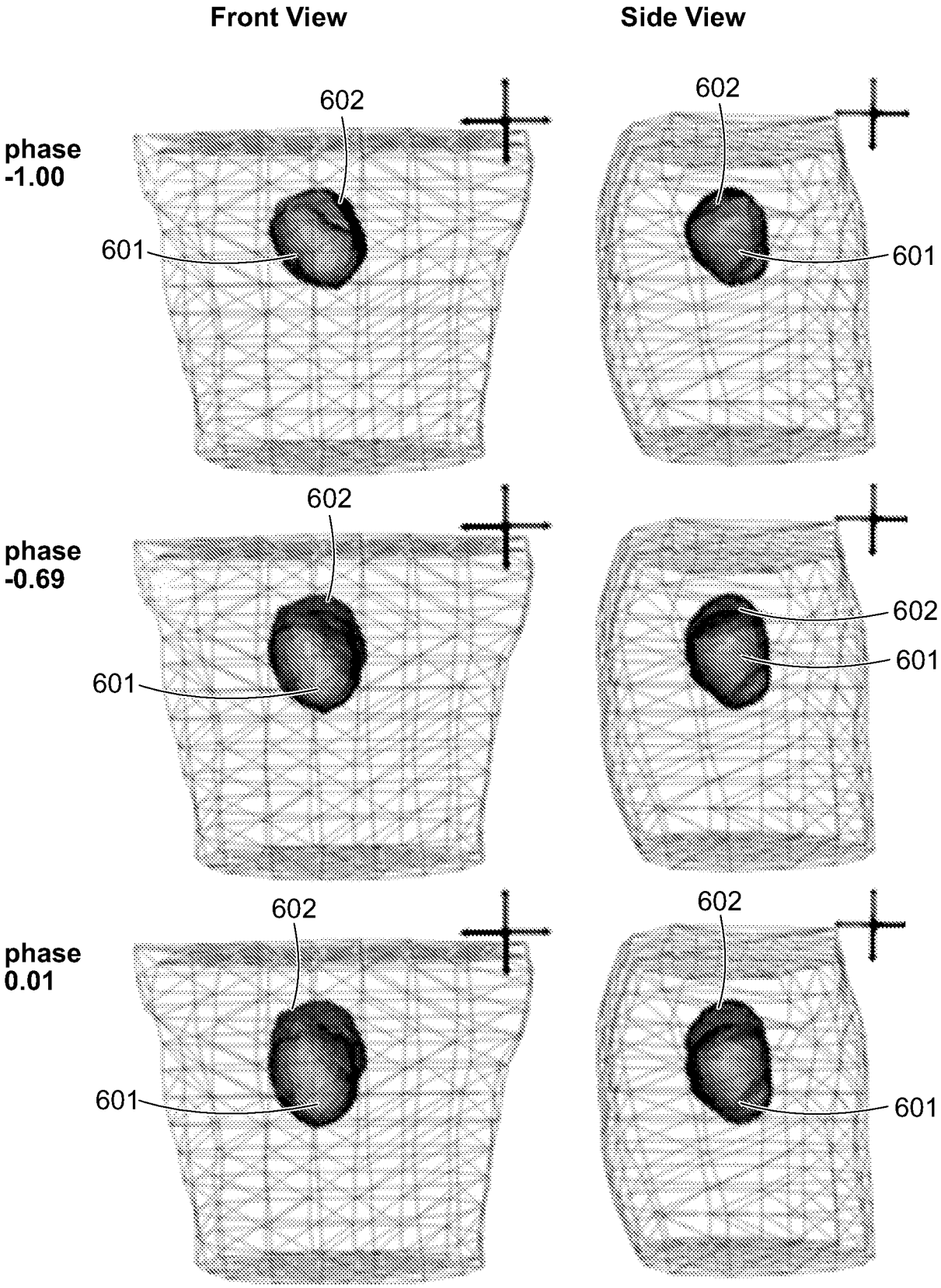

Front View
Side View
phase -1.00
602
601
602
601
phase -0.69
602
601
602
601
phase 0.01
602
601
602
601

FIG. 6

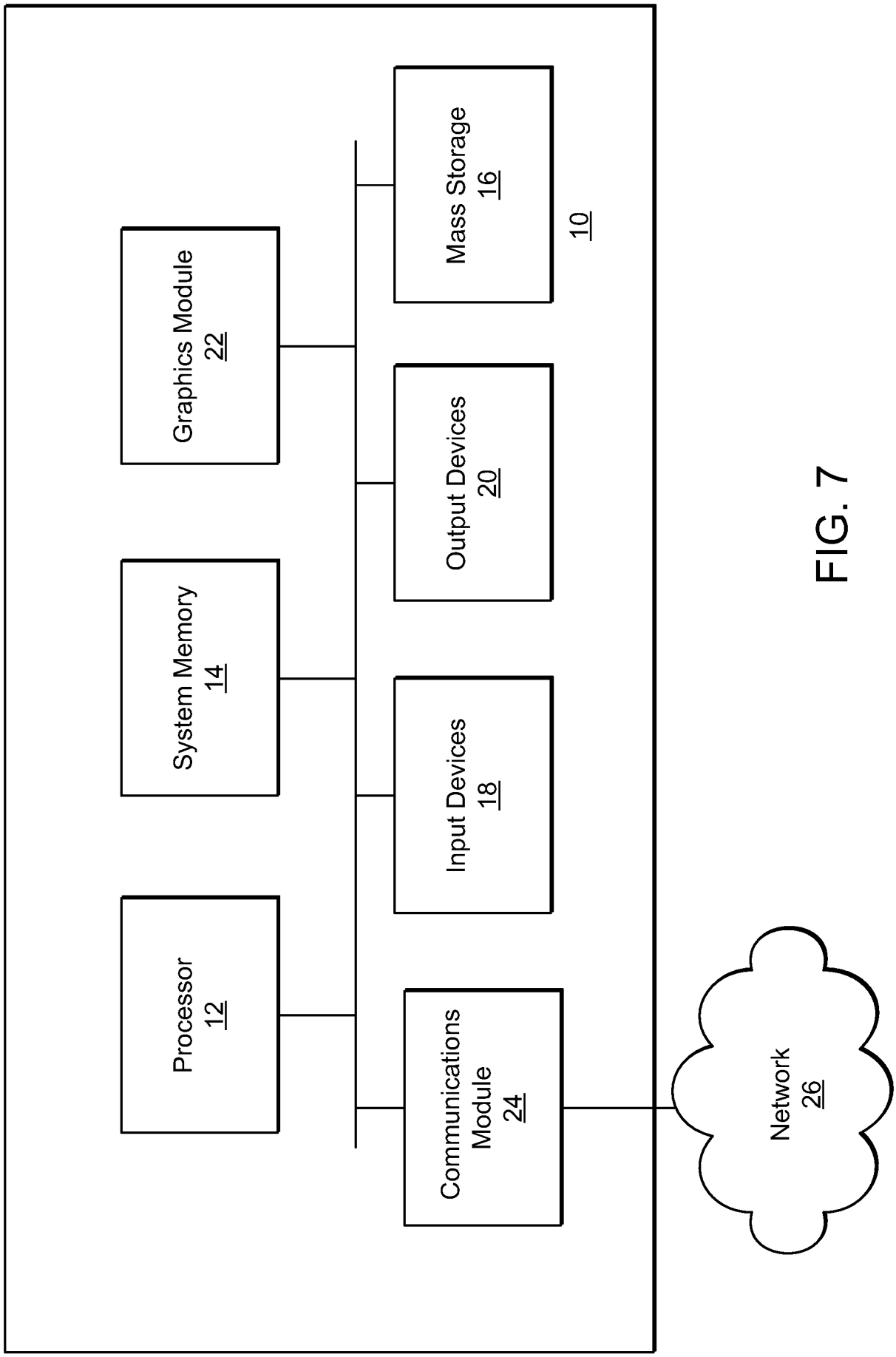

Mass Storage
16
10
Graphics Module
22
Output Devices
20
System Memory
14
Input Devices
18
Processor
12
Communications
Module
24
Network
26

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 16/49215

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - A61B 5/04 (2016.01)
CPC - A61B 5/0402
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8): A61B 5/04 (2016.01)
CPC: A61B 5/0402

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
CPC: A61B 5/00, A61B 5/04, A61B 5/0006, A61B 5/0245 (keyword limited search below)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatBase, Google Scholar, Google Patents; Search Terms: electrocardiogram, ECG, cardiac, heart, geometric change*, rotation*, translation*, volume model, forward model*, NORTHEASTERN UNIVERSITY, COLL-FONT, BROOKS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2012/0157822 A1 (Van Dam et al.) 21 June 2012 (21.06.2012) entire document especially Abstract, para [0012], para [0023], para [0033]-[0034], para [0072]-[0073]	1-20
Y	US 2011/0092809 A1 (Nguyen et al.) 21 April 2011 (21.04.2011) entire document especially Abstract, para [0128]-[0130], para [0136], para [0210]	1-20
A	US 2013/0096448 A1 (Brooks et al.) 18 April 2013 (18.04.2013) entire document	1-20

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
12 October 2016	15 NOV 2016
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Authorized officer: Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774