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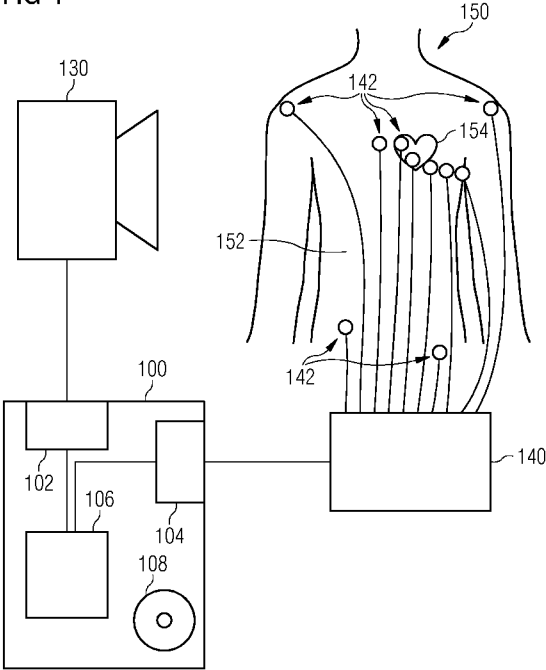
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FIG 1



(57) Abstract: A method includes obtaining image data of the heart of the patient, obtaining image data of a torso of the patient, obtaining positions of electrodes at the torso, obtaining a measured ECG signal measured at the patient using the electrodes, parameterizing of a model for estimating electrical potentials on the skin of the torso of the patient depending on cardiac activity, determining multiple simulated ECG signals for multiple activation patterns using the model, and determining the cardiac activation area of the heart based on comparing the multiple simulated ECG signals with the measured ECG signal.

ELECTROCARDIOGRAPHY BASED DETERMINATION OF A CARDIAC ACTIVATION AREA

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of European Patent Application No. EP23179803, filed June 16, 2023, the entire contents of which is incorporated by reference for all purposes as if fully set forth herein.

FIELD OF THE DISCLOSURE

[0002] The present disclosure relates generally to determining a cardiac activation area of a heart of a patient, and in particular to a method and a system for determining a cardiac activation area of a heart based on electrocardiography, e.g., for determining an area of ablation for ventricular tachycardia treatment.

BACKGROUND

[0003] Electrocardiography is a non-invasive medical means that can be used to represent and/or record the electrical activity of the heart of a patient. Electrocardiography is the process of producing an electrocardiogram, a recording of the heart's electrical activity through repeated cardiac cycles. An ECG apparatus measures electrical impulses generated by the heart and produces a visual representation of the heart's activity, called an electrocardiogram (ECG). The electrical impulses are detected by electrodes applied to the body of the patient. The electrodes detect electrical potentials at the corresponding positions where the electrodes are applied. The ECG includes several graphs that represent the detected electrical potentials in relation to each other.

[0004] ECGs can be used to diagnose a variety of heart conditions, including ventricular tachycardia. Ventricular tachycardia is a fast heart rhythm that originates in the ventricles, the lower chambers of the heart. During ventricular tachycardia, the heart can beat more than 100 times per minute, which can lead to symptoms such as dizziness, lightheadedness, and fainting. In some cases, ventricular tachycardia can be life-threatening. On an ECG, ventricular tachycardia can be identified by a wide, unusual-looking QRS complex (the combination of three of the graphical deflections seen on a typical electrocardiogram) that

typically lasts longer than 120 milliseconds. In ventricular tachycardia, this can be repeated in fast sequence. It is also possible to have isolated, wide and unusual-looking QRS complexes but that can be a sign of premature ventricular contraction (PVC) rather than ventricular tachycardia. The QRS complex represents the electrical activity that occurs when the ventricles contract to pump blood out of the heart. In ventricular tachycardia, the electrical impulses that control the ventricular contractions are abnormal, leading to the characteristic changes seen on the ECG.

[0005] In addition to providing a visual representation of the heart's electrical activity, ECGs can also help to identify the underlying cause of abnormal contractions, e.g., ventricular tachycardia, such as an underlying heart disease or electrolyte imbalance. Treatment for abnormal contractions like ventricular tachycardia can include medications, implantable devices such as pacemakers or defibrillators, or catheter ablation. Catheter ablation is a minimally invasive procedure in which a thin, flexible tube (catheter) is inserted into a blood vessel and guided to the heart. The catheter delivers radiofrequency energy or extreme cold to small areas of heart tissue that are causing abnormal electrical signals, creating small scars that interrupt the abnormal electrical activities responsible for abnormal contractions.

[0006] Electrocardiography plays an important role in guiding catheter ablation procedures, such as those used to treat ventricular tachycardia. During the procedure, the ECG can be monitored continuously to help identify the location of the abnormal electrical signals causing the ventricular tachycardia. By analyzing the ECG pattern, the exact location of the arrhythmia can be pinpointed, and the catheter can be guided to that area of the heart. Once the catheter is in the correct location, the ECG can be used to confirm that the abnormal electrical signals have been successfully interrupted by the ablation procedure.

[0007] However, precise determination of the location of the arrhythmia before performing the ablation procedure, i.e., a non-invasive technique without inserting any catheter, can improve success of treatment and can reduce risks during the ablation procedure, e.g., by improved guidance of the catheter.

[0008] The Background section of this document is provided to place embodiments of the present disclosure in technological and operational context, to assist those of skill in the art in understanding their scope and utility. Approaches described in the Background section could be pursued but are not necessarily approaches that have been previously conceived or pursued. Unless explicitly identified as such, no statement herein is admitted being prior art merely by its inclusion in the Background section.

SUMMARY

[0009] There is a need for improved techniques for determining the location of a cardiac activation area. In particular, there is a need for improved non-invasive techniques which enable determining the location of a cardiac activation area based on electrocardiography.

[0010] The following is a simplified summary of the disclosure for the purpose of providing a basic understanding to those skilled in the art. This summary is not a comprehensive overview of the disclosure and is not intended to identify key/critical elements of embodiments of the disclosure or to define the scope of the disclosure. The sole purpose of this summary is the presentation of some of the concepts disclosed herein in a simplified form as a prelude to the more detailed description that will be presented later.

[0011] Various techniques in connection with determining a location of a cardiac activation area based on electrocardiography are described below.

[0012] A method for determining a cardiac activation area of a heart of a patient based on electrocardiography, ECG, comprises obtaining image data of the heart of the patient as well as obtaining image data of a torso of the patient. Furthermore, according to the method, positions of electrodes at the torso are obtained. The electrodes can include skin electrodes that can be applied non-invasively. An ECG signal is obtained. The ECG signal, hereafter referred to as the "measured ECG signal", is measured on the patient using the electrodes in combination with for example an ECG apparatus. Based on the image data of the heart, the image data of the torso, the positions of the electrodes, and the measured ECG signal, a model is parameterized. The model is configured for estimating electrical potentials on the skin of the torso of the patient depending on cardiac activity. Multiple

simulated ECG signals for multiple activation patterns are determined using the model. The cardiac activation area of the heart is determined based on comparing the multiple simulated ECG signals with the measured ECG signal.

[0013] An ECG signal can comprise a 12-lead ECG. This can apply to the measured ECG signal as well as to each simulated ECG. In a 12-lead ECG, ten electrodes can be placed at the patient. The overall magnitude of the heart's electrical potential is then measured from twelve different angles ("leads") and is recorded over a period of time (usually ten seconds). In this way, the overall magnitude and direction of the heart's electrical depolarization is captured at each moment throughout the cardiac cycle.

[0014] According to various examples, a system for determining a cardiac activation area of a heart of a patient based on ECG is provided. The system comprises at least one interface and a control circuit. The system can comprise a computer system, e.g., a personal computer or server, including one or more processors as the control circuit, e.g., one or more central processing units (CPUs) or graphics processing units (GPUs).

[0015] The at least one interface is configured to obtain image data of the heart of the patient, obtain image data of a torso of the patient, obtain positions of electrodes at the torso, and obtain a measured ECG signal measured at the patient using the electrodes. The at least one interface can include one or more interfaces for data communication with imaging devices, for example cameras, computer tomography devices, sonography devices, angiography devices, x-ray devices, or any other medical or non-medical imaging device for capturing 2D or 3D images. Positions of the electrodes at the torso can be obtained based on image data of the torso captured by a stereo camera, or based on any other 3D scanning technologies, including e.g., optical, acoustic, laser, radar, or thermal scanning techniques. Positions of the electrodes at the torso can be obtained based on computer tomographic images. Positions of the electrodes at the torso can be obtained based on user input. The at least one interface can include an interface for data communication with an electrocardiograph providing for example a 12-lead ECG. The at least one interface can include an interface for communication with a database from which previously captured image data, positioning data and measured ECG signal data can be retrieved. In general, the at least one interface can include any type of interface for data

communication, for example via a Local Area Network (LAN), Wireless LAN (WLAN), Bluetooth (BT), Universal Serial Bus (USB) and the like.

[0016] The control circuit is configured to parameterize a model for estimating electrical potentials on the skin of the torso of the patient depending on cardiac activity. In particular, the model is parameterized based on the image data of the heart, the image data of the torso, the positions of the electrodes, and the measured ECG signal. By use of the parameterized model, the control circuit determines multiple simulated ECG signals for multiple activation patterns and determines the cardiac activation area of the heart based on comparing the multiple simulated ECG signals with the measured ECG signal.

[0017] For example, a measured 12-lead ECG, captured 3D medical images of the heart and the torso, and information on positions of the ECG electrodes on the torso can be input as input parameters into the system, i.e., made available to the control circuit, which provides a parameterizable generic model of a human's torso and heart. Parameters of the model relating to the location and orientation of the heart and the torso can be adapted based on the corresponding images. Based on the heart and torso anatomy, the system estimates the electrical potential on the torso and adapts parameters of the model such that similarity with the input 12-lead ECG is maximized. To do so, the system produces a simulated ECG signal, e.g., by estimating the electrical potential on the torso in the corresponding ECG electrodes positions based on the model. To estimate the electrical potential on the torso at the corresponding ECG electrode positions in the model, a sinus rhythm with normal activation of the myocardium can be assumed. The model can include further parameters which can be adapted such that the similarity with the input 12-lead ECG can be maximized. For example, the conduction velocity and/or electrical diffusivity of cardiac tissue can be varied until a QRS complex of the simulated ECG signals corresponds to a QRS complex of the measured ECG signal. In further examples, the electrical conductivity of torso tissue can be varied until signal amplitudes of at least some of the simulated ECG signals match to signal amplitudes of the corresponding measured ECG signal.

[0018] Furthermore, parameterizing of the model based on the generic model can comprise varying an orientation of the heart with respect to the torso and/or varying a placement of

the heart with respect to the torso for optimizing a match between at least some of the simulated ECG signals with the corresponding measured ECG signal.

[0019] The system can then estimate the electrical potential on the torso that corresponds to a variety of different activation patterns of the heart. The system can compare the simulated 12-leads ECG signals corresponding to the variety of different activation patterns with the measured 12-leads ECG signal and can determine which one of the simulated 12-leads ECG signals has the best matching to the measured 12-leads ECG signal. The activation pattern of best matching simulated 12-leads ECG signal can be used to determine the cardiac activation area of the heart.

[0020] In various examples, the system can further determine whether ECG signal variations of the simulated 12-leads ECG signals are sufficient to discriminate the underlying cardiac activation patterns from each other. If the simulated 12-leads ECG signals are not sufficient to distinguish cardiac activation patterns, i.e., two or more of the simulated 12-leads ECG signals are similar although they result from different cardiac activation patterns, the positions of the electrodes can be varied in the model and further simulated 12-leads ECG signals can be estimated for the variety of different activation patterns. This can be repeated until positions for the electrodes are found that result in sufficiently distinguishing simulated 12-leads ECG signals for the variety of different activation patterns. The thus found positions for the electrodes can be output and the positions of the electrodes at the torso can be adapted accordingly. Then, the parameterization can be repeated with the new electrode positions and a correspondingly measured ECG signal.

[0021] A computer program or a computer program product or a computer-readable storage medium comprises electronically readable control information, e.g., program code, which can be loaded and executed by a control circuit, e.g., a processor. When the control circuit executes the program code, a method for determining a cardiac activation area of a heart of a patient based on electrocardiography is implemented. The method comprises obtaining image data of the heart of the patient, obtaining image data of a torso of the patient, obtaining positions of electrodes at the torso, obtaining a measured ECG signal measured at the patient using the electrodes, and parameterizing of a model for estimating

electrical potentials on the skin of the torso of the patient depending on cardiac activity. The model is parameterized based on the image data of the heart, the image data of the torso, the positions of the electrodes, and the measured ECG signal. The method further comprises determining multiple simulated ECG signals for multiple activation patterns using the model and determining the cardiac activation area of the heart based on comparing the multiple simulated ECG signals with the measured ECG signal.

[0022] The features set out above and features that are described below can be used not only in the corresponding combinations explicitly set out, but also in further combinations or in isolation, without departing from the scope of protection of the present disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] The present disclosure will now be described more fully hereinafter with reference to the accompanying drawings, in which embodiments of the disclosure are shown.

However, this disclosure should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the disclosure to those skilled in the art. Like numbers refer to like elements throughout.

[0024] FIG. 1 shows schematically a system for determining a cardiac activation area of a heart of a patient according to an embodiment.

[0025] FIG. 2 is a flowchart of steps of a method for determining a cardiac activation area of a heart of a patient according to an embodiment.

DETAILED DESCRIPTION

[0026] The properties, features and advantages of this disclosure described above and the way in which they are achieved will become clearer and more clearly understood in association with the following description of the exemplary embodiments which are explained in greater detail in connection with the drawings.

[0027] For simplicity and illustrative purposes, the present disclosure is described by referring mainly to an exemplary embodiment thereof. In the following description,

numerous specific details are set forth in order to provide a thorough understanding of the present disclosure. However, it will be readily apparent to one of ordinary skill in the art that the present disclosure can be practiced without limitation to these specific details. In this description, well known methods and structures have not been described in detail so as not to unnecessarily obscure the present disclosure.

[0028] Unless otherwise expressly stated, it is in no way intended that any method set forth herein be construed as requiring that its steps be performed in a specific order, nor that with any apparatus, specific orientations be required. Accordingly, where a method claim does not actually recite an order to be followed by its steps, or that any apparatus claim does not actually recite an order or orientation to individual components, or it is not otherwise specifically stated in the claims or description that the steps are to be limited to a specific order, or that a specific order or orientation to components of an apparatus is not recited, it is in no way intended that an order or orientation be inferred, in any respect. This holds for any possible non-express basis for interpretation, including: matters of logic with respect to arrangement of steps, operational flow, order of components, or orientation of components; plain meaning derived from grammatical organization or punctuation, and; the number or type of embodiments described in the specification.

[0029] Various examples of the present disclosure relate to systems and methods for determining a cardiac activation area of a heart of a patient based on electrocardiography. The disclosed systems and methods allow a non-invasive identification of the cardiac activation area. Non-invasive identification of a cardiac activation area can be used for identification of a target site for ablation as part of for example ventricular tachycardia (VT) treatment. Generally, as will be described below, the target site or area can be approximately estimated by analyzing signal patterns of a 12-lead electrocardiogram (ECG). It has been found that the position of ECG electrodes affects the signal features especially in the precordial region. ECG electrodes are positioned following general rules based on population-average anatomic models. Furthermore, it has been found that there can be an uncertainty on the patient-specific anatomy, for example mutual position and size of the heart and the torso, and on the position of the ECG electrodes with respect to the patient's heart. This can limit precision of determining the target size or area. Additionally, there is intrinsic ambiguity in the ECG signal, for example when the early

activation is localized in basal or septal areas. The tissue abnormality that is responsible for VT re-entry could be localized in different anatomical structures occupying the same area, for example left or right ventricle. In this case, the ECG can contain features that are not clearly discriminative of the different scenarios. However, it can be important to know exactly what anatomical structure hosts the target for ablation, since this affects planning and execution of the ablation procedure.

[0030] Generally, in view of the above, personalized computational electrophysiological models can be applied to estimate areas of early activation from measured ECGs, for example 12-lead ECGs. For example, 3D imaging showing the patient's heart can be captured. 12-lead ECG measurements in sinus rhythm and/or during VT can be captured. Based on the 3D imaging of the heart and the 12-lead ECG, a computational model of electrophysiology can be built. The model can be capable of producing simulated 12-lead ECG signals. The area of early activation of the patient's heart can be inferred from the area of early activation computed by the computational model, when the simulated and measured ECG signals are matching.

[0031] As such, an exemplary system 100 for determining a cardiac activation area in connection with a patient 150 is shown in FIG. 1.

[0032] The system 100 can comprise one or more interfaces 102 for obtaining image data of the heart 154 and the torso 152 of the patient 150. The interface(s) 102 can be directly coupled to corresponding capturing device(s) 130. The image data can include 3D images. The capturing device 130 can include a magnetic resonance or computed tomography device, a sonography device, an x-ray device, or a camera device, for example a 3D camera system. Imaging techniques can include 3D echocardiography imaging, cardiac magnetic resonance (CMR) imaging, and cardiac-gated computed tomography (Cardiac CT) imaging. Cardiac CT examinations can include acquisitions with sufficient field of view that the torso 152 can be reconstructed via segmentation. In case of CMR, specific "localizer" acquisitions can be performed which depict the chest area so that the torso can be segmented. Additionally, positions of electrodes 142 of an ECG apparatus 140 can be obtained via the interface 102. The electrodes 142 can include skin electrodes attached to the torso 152, for example by use of adhesives or suction. The electrodes 142 can be

visible in computed tomography (CT) examinations since they can include metallic components. In magnetic resonance imaging (MRI), skin markers at the location of the electrodes can be used. As a result, the system 100 can obtain via the one or more interfaces 102 image data of the heart 154, image data of the torso 152, and information on the positions of the ECG electrodes 142 at the torso 152.

[0033] The system 100 can further comprise an interface 104 for obtaining an ECG signal from the ECG apparatus 140. The ECG apparatus 140 measures the ECG signal at the patient 150 using the electrodes 142. In particular, the ECG apparatus 140 can provide to the interface 104 a measured, for example, a 12-lead ECG signal based on the measurements performed at the patient 150 using the electrodes 142. Although the interface 104 is shown as a separate interface, it can be integrally defined with the interface(s) 102, i.e., the interface(s) 102, 104 can provide a coupling to the capturing device 130 and the ECG apparatus 140. Generally, the information from the capturing device 130 and the ECG apparatus 140 can be received directly from these devices as livestreams or can be retrieved from a database in which the information has been stored previously. The interfaces 102, 104 can include, for example, an interface to a local area network (LAN), an interface to a wireless LAN (WLAN) or any other standardized or custom specific data communication interface.

[0034] The system 100 can further comprise a control circuit 106 coupled to the interfaces 102, 104 such that the control circuit 106 can process the information obtained via the interfaces 102, 104. The control circuit 106 can comprise a processor, for example a digital general purpose central processing unit (CPU), graphics processing unit (GPU), network, or server along with memory for storing data and program code, for example random access memory (RAM), read only memory (ROM, and/or flash memory), and input/output (I/O) units for inputting and outputting information from/to a user interface and a data carrier 108, for example a hard disk, a CD-ROM and/or flash memory. As such, the system 100 can comprise a computer, for example a personal computer, a notebook, or a server. The data carrier 108 can comprise electronically readable control information stored thereon which can be loaded into the memory of the control unit 106 and which is configured to control the control unit 106 to process the information obtained via the interfaces 102, 104 as will be described below.

[0035] Based on a model, for example a generic electrophysiology model of a human's torso and heart, and the information on the obtained heart and torso anatomy, the control unit 106 estimates the electrical potential on the torso which maximizes the similarity with the measured 12-lead ECG. For example, the control unit 106 parameterizes the generic electrophysiology model based on the image data of the heart 154, the image data of the torso 152, the positions of the electrodes 142, and the measured 12-lead ECG. Parameters of the model which can be varied for parameterizing the model can include properties of the heart and the torso, in particular electrical properties of the tissue of the heart and the torso, as well as the position and/or orientation of the heart 154 within the torso 152. For example, the control circuit 106 can produce simulated ECG signals by "sampling" the electrical potentials on torso at the corresponding ECG electrode positions using the parameterized model. "Sampling" the electrical potentials on the torso using the parameterized model means that the control circuit 106 calculates, using the model, electrical potentials for those locations at the torso where the electrodes are arranged at the patient's torso. A corresponding simulated 12-lead ECG signal can then be derived from the electrical potentials at those locations. It is clear that, upon applying an activation pattern to the heart, at each electrode location a sequence of varying electrical potentials is sampled which indicates the voltage curve at that electrode location. Based on these simulated voltage curves, the simulated 12-lead ECG signal is determined. Parameterizing the model can be performed by varying the above parameters and comparing the corresponding simulated ECG signal with the measured ECG signal. The parameters are varied such that the matching between the simulated ECG signal and the measured ECG signal is maximized. During parameterization of the model, a "normal" activation pattern can be applied to the heart in the model, for example an activation pattern where the heartbeat activation starts in the sinus node of the heart and no additional ventricular activation occurs. However, depending on the measured ECG signal, another activation pattern can be applied during parameterization of the model that appear to be more appropriate, for example an activation pattern where the activation of the heartbeat has its origin in a ventricle, or an early activation occurs in a septal endocardial point.

[0036] As noted above, the voltage curves at the electrode locations depend on the type of activation pattern applied to the heart in the model. Therefore, when the model is

parameterized, the control unit 106 can determine multiple simulated 12-lead ECGs for multiple activation patterns using the parameterized model. The multiple activation patterns can include a normal activation of the myocardium starting in the septal endocardial, an early activation in a predefined set of septal endocardial points, and an early activation in a predefined set of non-septal endocardial points. The thus derived multiple simulated ECG signals for the multiple activation patterns can be compared by the control circuit 106 with the measured ECG signal and the activation pattern corresponding to the best matching simulated ECG signal can be assumed to correspond to the activation pattern acting in the patient's heart 152. Based on this activation pattern, a catheter ablation procedure can be planned.

[0037] Additionally, based on the plurality of simulated ECG signals, the control circuit 106 can determine whether the simulated ECG signals are sufficiently different from each other such that one of the activation patterns can be identified with sufficient certainty based on the simulated ECG signals. For example, if some of the simulated ECG signals are similar although they are based on significantly different activation patterns, it can be determined that the simulated ECG signals are not sufficiently different from each other for identifying the underlying activation pattern. In this case, the position of the electrodes can be varied in the parameterized model and further simulated ECG signals can be determined by applying the multiple activation patterns again. The control circuit 106 can then determine whether the further simulated ECG signals are sufficiently different from each other such that one of the activation patterns can be identified with sufficient certainty. This can be repeated until the simulated ECG signals sufficiently differ from each other. The thus determined positioning of the electrodes can be output to a user of the system 100 as a proposal to rearrange the electrodes 142 at the patient 150 to achieve more reliable information for ablation planning.

[0038] In the following, the above-described techniques will be described in more detail with reference to a method 200 shown as a flowchart in FIG. 2. The method steps of the method 200 can be performed by the control circuit 106 and can be defined in program code stored on a data carrier 108.

[0039] As explained above, in step 202, image data 252 of the heart 154 of the patient 150 is obtained. In step 204, image data 254 of the torso 152 of the patient 150 is obtained. In step 206, a measured ECG signal 256 is obtained. The measured ECG signal 256 can be output by the ECG apparatus 140 upon measurements at the patient 150 using the electrodes 142. In step 208, positions 258 of the electrodes 142 at the torso 152 are obtained. A generic model of a human torso and heart is provided in the control circuit 106 and is parameterized in step 210 based on the image data 252 of the heart 154, the image data 254 of the torso 152, the positions 258 of the electrodes 142, and the measured ECG signal 256. The model is capable to simulate or estimate electrical potentials on the skin of the torso depending on cardiac activity. A plurality of activation patterns can be provided in the control circuit 106 which can be used in connection with the model for activating and simulating cardiac activity. I.e. upon selecting an activation pattern, the model simulates electrical potentials on the skin of the torso, for example at a plurality of predefined points on the skin of the torso.

[0040] Parameterization of the generic model will be described in more detail in the following.

[0041] The generic model can be capable of producing ECG signals under varying configurations representing for example modified size and geometry of the heart, of the torso, the mutual arrangement in space, and positions of the ECG electrodes. Furthermore, physical properties can be considered and varied, in particular electrical properties. For example, a computational model of electrophysiology capable of estimating electrical potentials on the torso can be utilized. Methods to create such computational models are well known in the art. Additionally or as an alternative, a data-driven model of electrical potentials on the torso can be utilized.

[0042] In detail, given the input information (anatomical images of the heart and torso, ECG electrodes position, and a corresponding 12-lead ECG signal), a personalized computational model of electrophysiology can be defined by a discrete set of spatial locations, each associated with a set of (input) features, and for which variables of interests can be computed. For example, the generic model can comprise a finite elements representation of the heart and the torso. A discrete set of points can be organized in a

tetrahedral mesh representing the anatomy of the heart, and in a triangular mesh representing the anatomy of the torso. However, finite elements having other shapes can be utilized, e.g., tetrahedral meshes for the heart as well as for the torso. Each discrete point can be associated with, for example, a corresponding estimated electrical potential, a conduction velocity of corresponding tissue, and/or an electrical diffusivity of corresponding tissue.

[0043] As part of the personalization process, i.e., the parameterization of the model, the following can be carried out. Optimal physical properties of the cardiac tissue and the torso tissue can be estimated. For instance, the conduction velocity of the cardiac tissue can be iteratively varied until the generated/simulated ECG signal exhibits a QRS complex with the same duration as the measured ECG signal. Also, the conductivity of the torso can be modified to optimize the match of the simulated ECG signal amplitude in each lead compared to the measured ECG. The optimal orientation of the heart with respect to the torso can be estimated. This accounts for uncertainty in the image segmentation process. For instance, multiple options of arrangement in 3D space can be tested and simulated. The heart can be placed in multiple locations within the torso, and with multiple rotations, and the position and rotation that leads to the optimal match of the generated/simulated ECG signal with the measured ECG signal is selected as the optimal position and rotation.

[0044] The personalized parameterized virtual ECG model can include the optimal values of conduction velocities in the heart, and the optimal arrangement of heart and torso in space, which maximizes the match of the generated/simulated ECG with the measured ECG. One possible way to quantify the match is by computing the beat-by-beat correlation of each of the generated/simulated ECG lead signals with the corresponding measured ECG lead signals.

[0045] As a result, a parameterized model 260 is created.

[0046] Based on the parameterized model 260, in step 212 multiple simulated ECG signals 262-266 for multiple activation patterns can be determined. For example, corresponding simulated ECG signals 262-266 can be determined based on the electrical potentials on the skin of the torso. For example, a plurality of different activation patterns can be provided.

The activation patterns can be applied successively to the parameterized model 260 and for each applied activation pattern corresponding electrical potentials on the skin of the torso are simulated. Based on the simulated electrical potentials a corresponding simulated ECG signal 262-266 can be determined.

[0047] In more detail, the parameterized ECG model can be used to produce multiple variations of 12-lead ECG signals, corresponding to different activation patterns. For example, sinus rhythm ECG signals can have been originally provided as an input to the model, so the personalized parameterized ECG model is optimized to match sinus rhythm ECG signals. In sinus rhythm, normal activation of the myocardium generally starts in the septal endocardium, then proceeds to activate the left ventricular and right ventricular endocardia, and finally proceeds to the free walls and epicardia. The precise activation sequence can be unknown since it cannot be directly inferred from surface ECG measurements. Nonetheless, multiple different hypotheses can be formulated and tested with the parameterized ECG model. For example, early activation in a sparse set of septal endocardial points (either randomly selected or according to predefined data, e.g., from literature), i.e., in the ventricular endocardium, can be simulated. In further examples, early activation in a sparse set of septal and non-septal endocardial points (either randomly selected or according to predefined data, e.g., from literature), i.e., in the ventricular epicardium, can be simulated.

[0048] The parameterized model can then be used to produce a library of simulated ECG signals 262-266, each corresponding to a different activation pattern. In step 218, one of the simulated ECG signals in the library is selected as the best matching to the measured ECG signal. For example, the matching can be quantified by calculating the average or minimum correlation between all the simulated ECG leads and the corresponding measured ECG leads. The activation pattern of the best matching simulated ECG signal can be considered to represent the activation pattern that led to the measured ECG signal. Based on this activation pattern of the best matching simulated ECG signal, an early activation area of the heart 154 of the patient 150 can be determined.

[0049] In various examples, the library includes ECG signals generated by varying all variables in the ECG model (size and position of the heart and the torso, physical

properties of the cardiac tissue). A simulated ECG signal can be identified as the best match to the measured ECG signal in two steps. First, a subset of simulated ECG signals is extracted from the library based on the similarity between the size and position of the heart and torso extracted from the input 3D medical images and used for the generation of the signals in the library. Then, the best signal from the subset is selected based on a matching metric described above.

[0050] Before or in addition to determining the best match between the simulated ECG signal and the cardiac activation area, the method can be further improved by changing the positioning of the electrodes.

[0051] To accomplish this, in step 214, an average matching metric dependent on the simulated ECG signals 262-266 and/or the measured ECG signal 256 can be determined, and depending on the average matching metric, the position of the electrodes in the model can be varied and further multiple simulated ECG signals can be simulated for the various activation patterns.

[0052] Generally, the library of simulated ECG signals contains multiple signals which can be compared with each other. For example, the comparison can be performed by quantifying the match as described above to identify the best matching ECG signal. The matching between each pair of simulated ECG signals in the library can be computed and an average matching metric can be computed for the entire library. Additionally, or as an alternative, a matching metric can be computed between the measured ECG signal and any simulated ECG signal from the library. Also in this case, an average matching metric can be computed for the entire library. In further examples, the average matching metric can be computed only for the k nearest neighbors, i.e., the k simulated ECG signals in the ECG library with the best match to the measured ECG signal.

[0053] If the matching metric for the library exceeds a set threshold, this means that the multiple simulated ECG signals match very well with each other though they are based on different activation patterns. Consequently, different activation patterns may not be identified with high confidence based on the ECG signals because they are not significantly different from each other. Similarly, if the number k of nearest neighbors that

result in a matching metric that exceeds a set threshold is greater than a given value $k_{\max}$, this means that these k simulated ECG signals do not significantly differ from each other even though they are based on different activation patterns. If such matching is determined in step 220, better ECG electrode positions can be determined in step 216. For example, each ECG electrode position in the model can be displaced on the torso surface by a fixed distance (e.g., randomly selected) in one direction (e.g., randomly selected). For each new set of ECG electrode positions, the method can be repeated starting at step 208, with the new set of ECG electrode positions replacing the positions 258 obtained from the image data. It should be noted that the "real world" conditions can remain unchanged, at least for the time being. Thus, further multiple simulated ECG signals are computed with the same multiple activation patterns as in the previous pass (steps 208 to 212). A new library of simulated ECG signals 262-266 is populated. The matching metric for each pair of simulated ECG signals in the new library is computed (step 214), and the average matching metric for the library is derived. If the matching metric for the library exceeds the set threshold (step 220), the new ECG electrodes position is discarded and a further repositioning of the electrodes in the model can be performed (step 216). Varying the positions of the electrodes in step 216 can comprise for example, varying the position of at least one of the electrodes, removing one of the electrodes, and/or including one or more additional electrodes at additional positions.

[0054] Generally, new ECG electrode positions can be generated in the model until the matching metric of the library is below the set threshold, for at least one of the ECG electrodes positions. Additionally, or alternatively, new ECG electrode positions can be generated until a certain number of proposals have been generated, irrespective of the corresponding library matching metric. If at least one set of ECG electrode positions is found, for which the corresponding library matching metric is below the set threshold, then that set of ECG electrode positions is output to the user. If no new set of ECG electrode positions is found for which the library matching metric is below the set threshold, then no alternative set of ECG electrode positions is output to the user, and the ECG electrode positioning as captured at the torso can be maintained. In some examples, the sets of ECG electrode positions for which the library matching metric is minimal across all proposed ECG electrodes positions can be output to the user.

[0055] The user can then reposition the electrodes at the torso 152 of the patient 150 and the method can then be repeated, at least starting with obtaining the positions 258 of the electrodes at the torso 152 in step 208.

[0056] As mentioned above, the system can propose not only alternative positions of the existing ECG electrodes, but also addition or removal of ECG electrodes. This can be achieved for instance as follows.

[0057] All simulated ECG signals in the library corresponding to the multiple activation patterns can be considered. For each simulated ECG signal, the computed electrical potentials in each point of the torso surface are considered. For each torso point, a lead is defined where the torso point acts as the positive pole, while the opposing pole is the average potential on the torso, e.g., determined based on an average potential of the computed electrical potentials. For each lead, one time-invariant feature is extracted, for example the QRS time integral.

[0058] As a result, for each simulated ECG signal in the library a vector of features (e.g., the QRS time integral) is determined, with the number of elements equal to the number of points on the torso. Next, a Principal Component Analysis (PCA) is applied on the vectors, for example a Karhunen-Loeve transform, to approximate the space of vectors in the library as the linear combination of a small set of generator vectors (e.g., 3). For each generator vector, two or more multiples (e.g., with coefficients +1 and -1) are considered. For each multiple of each generator vector, the torso leads with the largest feature (e.g., QRS time integral) are localized, and marked as candidate location for an ECG electrode. Depending on the number of generator vectors selected in the above process, a number of ECG electrodes can be recommended that can be larger or smaller than the original number. Also, their optimal location on the torso can be recommended.

[0059] Once a new library is created, based on the new ECG electrode positions, the simulated ECG signal in the library that best matches the measured ECG signal is identified. If the number of electrodes has been modified, then the matching metric can be defined based on the common leads in the measured ECG and in the new simulated ECG signals.

[0060] To sum up, the above-described techniques allow to quantify whether the ECG electrodes as positioned on the torso of a patient can allow the proper discrimination between different activation patterns. Additionally, they recommend updated positions of the ECG electrodes for the specific goal of optimizing the discrimination of different activation patterns.

[0061] A typical clinical workflow using the above techniques can comprise the following.

[0062] The electrodes 142 of the ECG apparatus 114 are attached to the patient 150 in a manner known in the art. For example, ten electrodes can be placed on the patient 150 to record a 12-lead ECG over a period of time, such as 10 seconds, as a measured ECG signal. 3D images of the torso 152 and heart 154 of the patient 150 can be acquired using, for example, magnetic resonance or computed tomography, sonography, x-ray, or optical techniques. For example, 3D echocardiography, cardiac magnetic resonance, or cardiac computed tomography can be used. In addition, the positioning of the electrodes 142 on the patient 150, particularly on the torso 152 and in spatial relation to the heart 154, can be obtained using the above acquisition techniques. The image data of the heart and the image data of the torso, as well as the positions of the electrodes on the torso, are provided to the system 100. Electrocardiography is performed and an ECG is generated. The measured ECG signal is provided to the system 100.

[0063] The information listed above can be provided to the system 100 in real time or near real time or can be recorded and provided to the system 100 "off-line".

[0064] The system 100 performs the method described above in connection with FIG. 2. As described above, the system 100 can determine a better arrangement for the electrodes 142 and can provide a corresponding recommendation to an operator of the system 100. Based on the recommendation, the operator can rearrange the electrodes 142 as determined by the system 100, can include additional electrodes, or can remove some of the electrodes 142. With the new arrangement of the electrodes, an electrocardiography can again be performed, producing a further ECG signal. The further ECG signal is provided to the system 100. The system can recommend a further rearrangement of the electrodes and the

process can be repeated. However, if the process converges, further rearrangement of the electrodes can not be recommended by the system 100 or can be aborted by the operator.

[0065] As a result, an accurate model of the patient's heart within the patient's torso is achieved, and the system can output an activation pattern of the heart 154 that produces an ECG signal which corresponds to the ECG signal measured with the electrodes 142 in the appropriate positions determined above.

[0066] The activation pattern can be output by the system 100. For example, the system 100 can output at which point or at which points of the heart 154 a heartbeat is activated. For example, the activation pattern can indicate a ventricular activation. Based on the activation pattern, a physician can determine how to treat an abnormal behavior of the heart. For example, the physician can recommend an ablation. Since each activation pattern is based on the specific arrangement of one or more activation points in the model of the heart 154, a physician can determine an ablation strategy to deactivate such points.

[0067] Also during ablation, the model of the heart 154 within the torso 152 can be used to monitor the response of the heart 154 to ablation.

[0068] Generally, all terms used herein are to be interpreted according to their ordinary meaning in the relevant technical field, unless a different meaning is clearly given and/or is implied by the context in which they are used. All references to a/an/the element, apparatus, component, means, step, etc. are to be interpreted openly as referring to at least one instance of the element, apparatus, component, means, step, etc., unless explicitly stated otherwise. The steps of any method disclosed herein need not be performed in the exact order disclosed, unless a step is explicitly described as following or preceding another step and/or where it is implicit that a step must follow or precede another step. Any feature of any of the embodiments disclosed herein can be applied to any other embodiment, where appropriate. Likewise, any advantage of any of the embodiments can apply to any other embodiment and vice versa. Other objectives, features and advantages of the enclosed embodiments will be apparent from the description. As used herein, the term “configured to” means set up, organized, adapted, or arranged to operate in a particular way; the term is synonymous with “designed to”. As used herein, the term

“substantially” means nearly or essentially, but not necessarily completely; the term encompasses and accounts for mechanical or component value tolerances, measurement errors, random variation, and similar sources of inaccuracy.

[0069] The present disclosure can, of course, be carried out in ways other than those specifically set forth herein without departing from essential characteristics of the disclosure. The present embodiments are to be considered in all respects as illustrative and not restrictive, and all modifications coming within the meaning and equivalency range of the appended claims are intended to be embraced therein.

What is claimed is:

1. A method for determining a cardiac activation area of a heart of a patient based on electrocardiography, ECG, the method comprising:

obtaining image data of the heart of the patient;

obtaining image data of a torso of the patient;

obtaining positions of electrodes at the torso;

obtaining a ECG signal measured at the patient using the electrodes;

parameterizing a model for estimating electrical potentials on the skin of the torso of the patient depending on cardiac activity, wherein the model is parameterized based on the image data of the heart, the image data of the torso, the positions of the electrodes, and the measured ECG signal;

determining multiple simulated ECG signals for multiple activation patterns using the model; and

determining the cardiac activation area of the heart based on comparing the multiple simulated ECG signals with the measured ECG signal.

2. The method of claim 1, wherein the parameterizing the model is based on a generic model configured to provide ECG signals based on at least one of:

a size of the heart,

a geometry of the heart,

a size of the torso,

a geometry of the torso,

an arrangement of the heart with respect to the torso, and

an arrangement of the positions of the electrodes.

3. The method of claim 2, wherein the generic model is configured to estimate electrical potentials on the torso based on a computational model of electrophysiology.

4. The method of claim 2, wherein

the generic model comprises a mesh representation of the heart and/or the torso,

and

each mesh vertex is associated with at least one of (i) a corresponding estimated electrical potential, (ii) a conduction velocity of corresponding tissue, and (iii) an electrical diffusivity of corresponding tissue.

5. The method of claim 2, wherein parameterizing of the model based on the generic model comprises at least one of:

varying a conduction velocity and/or electrical diffusivity of cardiac tissue until a QRS complex of the simulated ECG signals corresponds to a QRS complex of the measured ECG signal, and

varying the electrical conductivity of torso tissue until signal amplitudes of at least some of the simulated ECG signals match to signal amplitudes of the corresponding measured ECG signal.

6. The method of claim 2, wherein parameterizing of the model based on the generic model comprises at least one of:

varying an orientation of the heart with respect to the torso for optimizing a match between at least some of the simulated ECG signals with the corresponding measured ECG signal, and

varying a placement of the heart with respect to the torso for optimizing a match between at least some of the simulated ECG signals with the corresponding measured ECG signal.

7. The method of claim 2, wherein the generic model is configured to estimate electrical potentials on the torso based on a data-driven model.

8. The method of claim 1, wherein the multiple activation patterns comprise at least one of:

a normal activation of the myocardium starting in the septal endocardium,
early activation in a predefined set of septal endocardial points,
early activation in a predefined set of non-septal endocardial points, and
early activation in a predefined set of non-endocardial points.

9. The method of claim 1, wherein the ECG signal comprises a 12-lead ECG.

10. The method of claim 1, further comprising:
determining an average matching metric based on the simulated ECG signals and/or the measured ECG signal; and
depending on the average matching metric, varying a position of the electrodes in the model and simulating further multiple simulated ECG signals for the various activation patterns using the model.

11. The method of claim 10, further comprising:
repeating the steps of determining the average matching metric, varying the position of the electrodes, and simulating further multiple ECG signals if the average matching metric exceeds a predefined threshold.

12. The method of claim 10, wherein determining the average matching metric comprises determining the average matching metric based on matching metrics for each pair of the simulated ECG signals.

13. The method of claim 10, wherein determining the average matching metric comprises determining the average matching metric based on matching metrics for each pair of a predefined number of the simulated ECG signals having the best match with respect to the measured ECG signal.

14. The method of claim 10, wherein the step of varying the position of the electrodes comprises at least one of:
varying the position of at least one of the electrodes,
removing one of the electrodes, and
including an additional electrode at an additional position.

15. A system for determining a cardiac activation area of a heart of a patient based on electrocardiography, ECG, the system comprising:
at least one interface configured to:
obtain image data of the heart of the patient,
obtain image data of a torso of the patient,

obtain positions of electrodes at the torso, and
obtain a measured ECG signal measured at the patient using the electrodes, and
a control circuit configured to:

parameterize a model for estimating electrical potentials on the skin of the torso of the patient depending on cardiac activity, wherein the model is parameterized based on the image data of the heart, the image data of the torso, the positions of the electrodes, and the measured ECG signal,

determine multiple simulated ECG signals for multiple activation patterns using the model, and

determine the cardiac activation area of the heart based on comparing the multiple simulated ECG signals with the measured ECG signal.

16. The system of claim 15, wherein the control circuit is configured to perform the method of claim 1.

17. A computer program product comprising a program that is directly loadable into a memory of a programmable control circuit, comprising programming for executing all steps of the method according to claim 1 when the program is executed in a control circuit.

18. A non-transitory computer-readable medium including executable instructions that when executed by a processor cause the processor to perform to perform the method according to any of claim 1 when used in a control circuit.

FIG 1

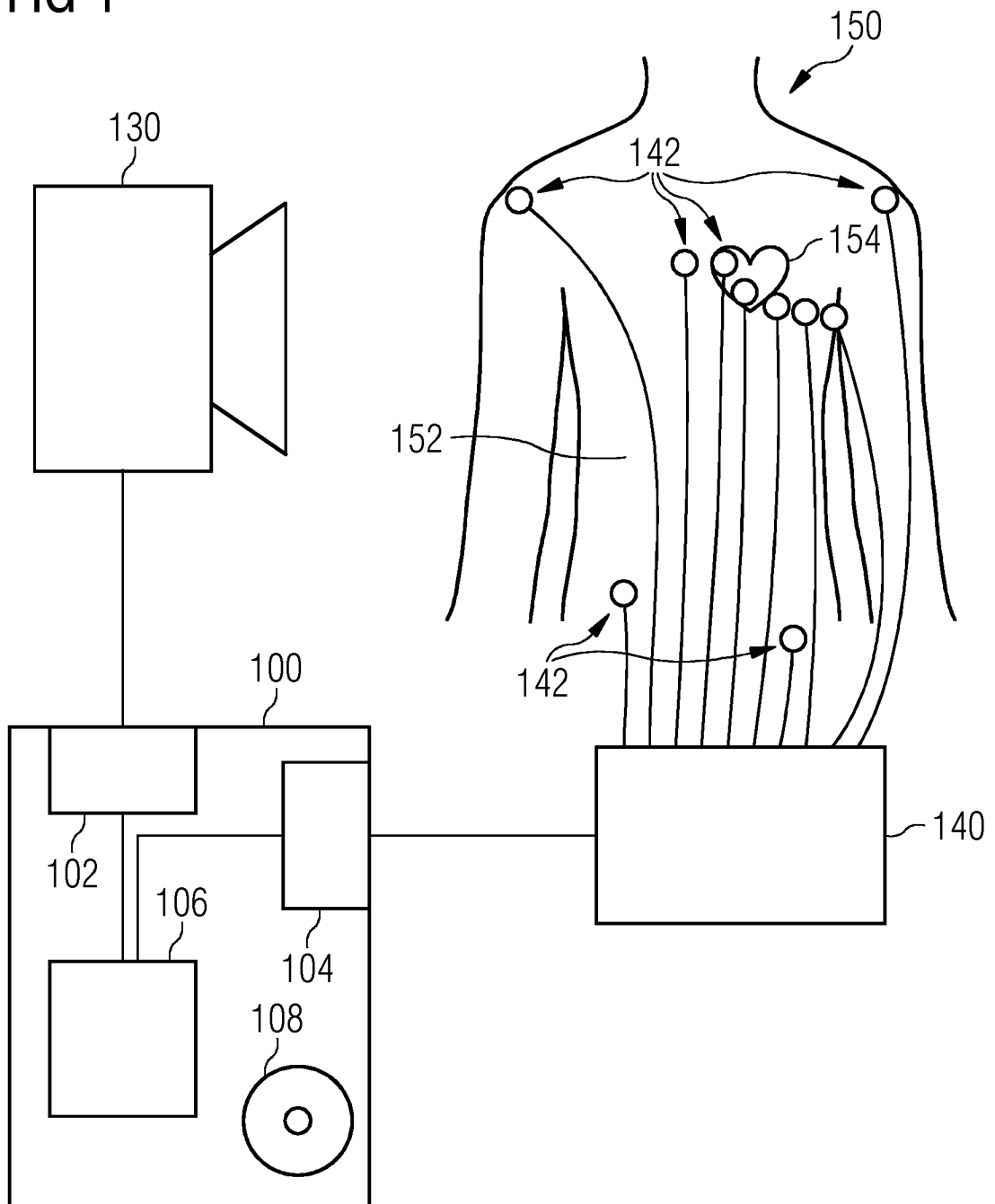
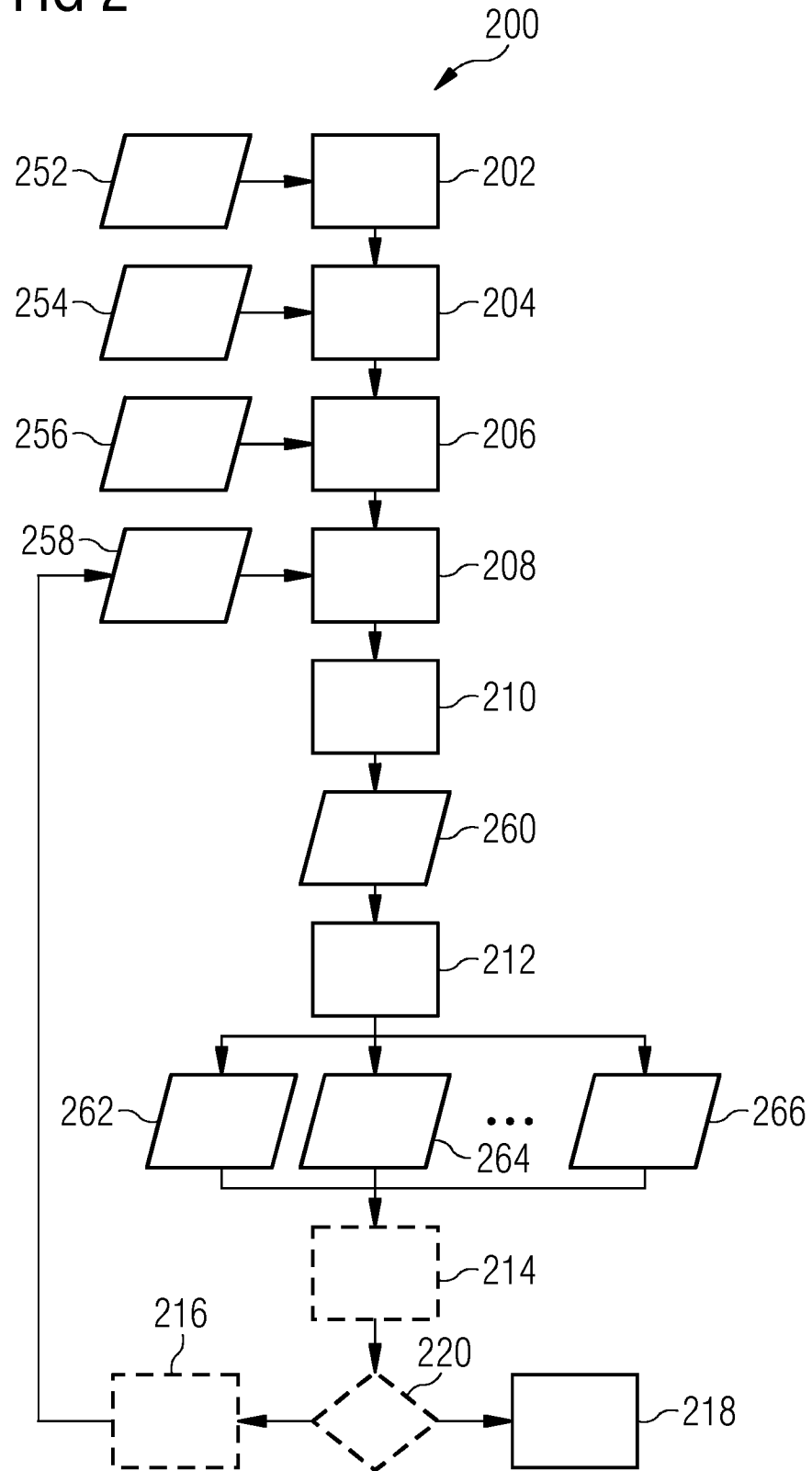


FIG 2



INTERNATIONAL SEARCH REPORT

International application No
PCT/US2024/034010

A. CLASSIFICATION OF SUBJECT MATTER INV. A61B5/00 A61B5/318 A61B5/349 G16H50/50 ADD.		
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) A61B G16H Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2015/153832 A1 (SIEMENS AG [DE] ; SIEMENS CORP [US]) 8 October 2015 (2015-10-08)	1 - 8, 15 - 18
Y	paragraphs [0004] - [0006] paragraphs [0021] - [0036] paragraphs [0053] - [0070] -----	6, 9 - 14
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☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* 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 "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "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 10 September 2024		Date of mailing of the international search report 16/09/2024
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Loveniers, Kris

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2024/034010

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
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Information on patent family members

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