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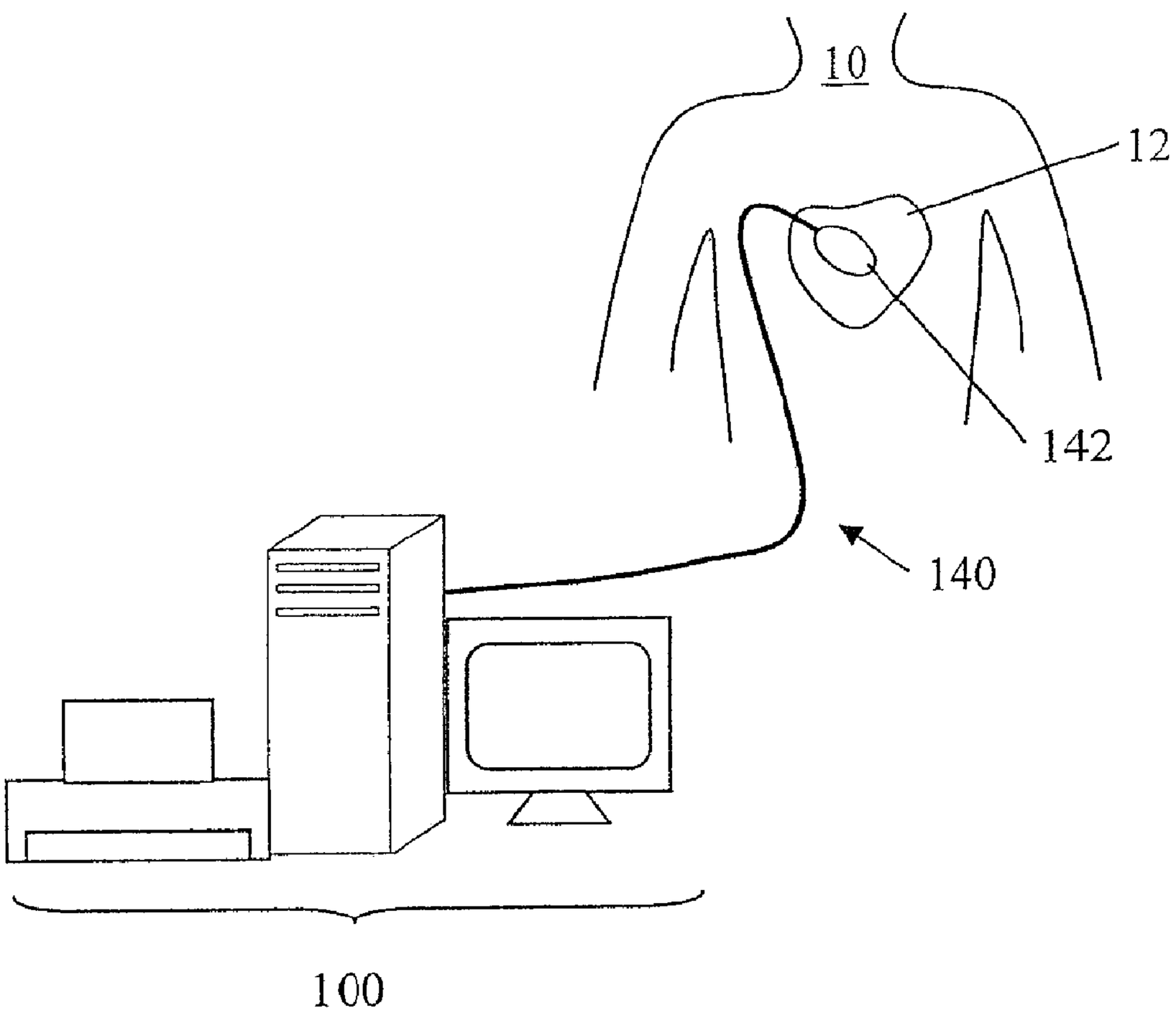
(54) **Titre : PROCEDE ET DISPOSITIF DE DETERMINATION ET DE PRESENTATION DE DENSITES DE CHARGE DE SURFACE ET DIPOLAIRES SUR DES PAROIS CARDIAQUES**

(54) **Title: METHOD AND DEVICE FOR DETERMINING AND PRESENTING SURFACE CHARGE AND DIPOLE DENSITIES ON CARDIAC WALLS**



(57) **Abrégé/Abstract:**
The invention discloses a method, a system, a computer program and a device for determining the surface charge and/or dipole densities on heart walls in order to locate the origin(s) of cardiac arrhythmias.

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(54) Title: METHOD AND DEVICE FOR DETERMINING AND PRESENTING SURFACE CHARGE AND DIPOLE DENSITIES ON CARDIAC WALLS

(57) Abstract: The invention discloses a method, a system, a computer program and a device for determining the surface charge and/or dipole densities on heart walls in order to locate the origin(s) of cardiac arrhythmias.

Method and Device for determining and presenting surface charge and dipole densities on cardiac walls

The invention discloses a method, a system, a computer program and a device for determining the surface charge and/or dipole densities on heart walls in order to locate the origin(s) of cardiac arrhythmias.

For localizing the origin(s) of cardiac arrhythmias it is common practice to measure the electric potentials located on the inner surface of the heart by electrophysiological means within the patient's heart. For example, for this purpose electrode catheters can be inserted into the heart and moved around while recording cardiac potentials during normal heart rhythm or cardiac arrhythmia. If the arrhythmia has a regular activation sequence, the timing of the electric activation measured in voltages at the site of the electrode can be integrated when moving the electrode around during the arrhythmia, to create a threedimensional map of the electric activation. By doing this, information on the localization of the source of arrhythmia(s) and mechanisms, ie. reentry circuits, can be diagnosed to initiate or guide treatment (radiofrequency ablation). This mapping procedure is often aided by computer systems generating three dimensional maps of catheter positions by localizing the catheter with the help of magnetic fields (the so called Carto System) or transthoracic impedances (by Localisa and NavX). Because all the points of such maps are obtained by electrode positions in contact with the cardiac surface, this mapping system is called contact mapping. It has the inherent limitation that cardiac activation can only be assessed simultaneously at the points in contact with the myocardium. Hence, an instant map of the entire cardiac activation is impossible because the entire heart chamber cannot be contacted without compromising blood circulation. An instant mapping of the simultaneous electric activation of the heart chamber, however, might be of advantage in unstable arrhythmias of short duration, rendering the mapping procedures (moving the electrode around during the arrhythmia) too long. In addition, an instant map of cardiac electric activation might be of advantage during irregular arrhythmias or arrhythmias with non-constant activation sequences that render integration of activation times from contact mapping impossible. Finally, instant maps of cardiac activation are probably also faster and easier obtained, than a contact map gener-

ated by time consuming catheters movements to different areas of the heart in all sorts of cardiac arrhythmias.

The disadvantage of contact mapping can be overcome by "non-contact mapping", which allows for mapping cardiac activation of a heart chamber simultaneously without contact to the cardiac wall. For this purpose, for instance, a multi electrode array mounted on an inflatable balloon can be inserted into the heart. The geometry of the heart chamber is obtained either (i) by reconstruction of a contact map, which is obtained from integration of movements with an electrode catheter within the heart chamber, or (ii) by importing imaging data from computed tomography or MRI (magnetic resonance imaging). Once the geometry of the cardiac chamber is outlined in a map the information of a simultaneous recording of cardiac farfield potentials (unipoles) by the multi electrode array can be extrapolated to the desired cardiac map using advanced mathematical methods. This non-contact mapping has the advantage that it provides the entire electric activation measured by farfield unipolar potentials either in sinus rhythm or during arrhythmia without the need for moving an electrode catheter around the cardiac chamber. This allows for a beat to beat analysis of cardiac activation and, therefore, unstable, irregular or multifocal arrhythmias can be tracked and treated. However, the disadvantage of non-contact mapping is that it relies on farfield potentials, which do not allow for the same precision in localization as contact mapping (i.e. measuring local electrograms (potentials) of cardiac activation by touching the endocardium at the site of interest with a mapping electrode). Furthermore, non-contact mapping is more prone to artifact generation and interference from potentials generated by cardiac repolarization and adjacent heart chambers (atria/ventricles). These drawbacks can be overcome to a certain extent with several filtering techniques. One the other side, in many cases these drawbacks also render the localization of cardiac arrhythmias a time-consuming frustrating intervention.

Therefore, the advantages of non-contact mapping, i.e. the instant cardiac activation maps, have to be balanced against the disadvantages, i.e. the decreased spatial resolution due to recording of far field signals, filtering of artifacts, etc.

Finally, another method for the non-invasive localization of cardiac arrhythmias is body surface mapping. In this technique multiple electrodes are attached to the entire surface of the thorax and the information of the cardiac electrograms (surface ECG) is measured in volt-

ages integrated to maps of cardiac activation. Complex mathematical methods are required in order to determine the electric activation in a heart model, for instance, one obtained from CT or MRI imaging giving information on cardiac size and orientation within the thoracic cavity.

The disadvantage of both mapping methods, i.e. contact and non-contact types, is the representation of the electric activity of the heart by means of potentials, that are the result of a summation of electric activities of many cardiac cells. The integration of all these local electric ion charges generated by the cardiac cells provides for the potentials that are measured by current mapping systems.

Therefore, it is an object of the present invention to provide a method, a system, a program and a device for improving precision, accuracy and spatial resolution of cardiac activation mapping, when compared to prior art systems.

It was surprisingly found that the use of surface charge and/or dipole densities and in particular their distribution in a heart chamber is a much better indicator of cardiac arrythmias than electric potentials in the heart.

In a first aspect, the present invention relates to a method for determining a database table of surface charge densities (ρ) of at least one given heart chamber, the surface charge density information comprising a table (data values) $\rho(P, t)$, wherein:

i) the position $P=(x,y,z)$ of a point at the wall of the heart is defined in x, y ,z-coordinates,

ii) t is the time of measurement for said surface charge density, and

iii) ρ is the surface charge density at said time t and said position P derived from a measured electric potential from a given heart chamber,

comprising the following steps:

a) measuring and/or calculating one or more electric potential(s) V_e in one or more position(s) P at the cardiac wall at a given time t,

b) transforming V_e into said charge density $\rho(P,t)$ by using an algorithm suitable for transforming an electric potential into surface charge density.

In an alternative aspect, the present invention relates to a method for determining a data-

base table of dipole densities $\nu(P,t)$ of at least one given heart chamber, the dipole density information comprising a table (data values) $\nu(P, t)$, wherein:

i) the position P=(x,y,z) of a point at the wall of the heart is defined in x, y ,z-coordinates,

ii) t is the time of measurement for said dipole density, and

iii) ν is the dipole density at said time t and said position P derived from a measured electric potential from a given heart chamber,

comprising the following steps:

a) measuring and/or calculating one or more electric potential(s) V_e in one or more position(s) P at the cardiac wall at a given time t,

b) transforming V_e into said dipole density $\nu(P,t)$ by using an algorithm suitable for transforming an electric potential into dipole density.

Preferably, the electric potential(s) V_e is (are) determined by contact mapping. Equally preferred the electric potential(s) V_e is (are) determined by non-contact mapping.

In a preferred embodiment, the above mentioned algorithm method for transforming said V_e into surface charge density (ρ) or dipole densitiy (ν) in step b) above employs the boundary element method (BEM).

It is preferred that the geometry of the probe electrode is ellipsoidal or spherical.

In preferred embodiment, said measured potential(s) V_e is (are) transformed into surface charge densities ρ using the following equation:

$$V_e(P) = -\frac{1}{4\pi}\int_{S_e}\frac{\rho(P')}{|P'-P|}d\sigma(P') \quad (4)$$

In an alternative preferred embodiment, said measured potential(s) V_e is (are) transformed into dipole densities ν using the following equation:

$$V_e(P) = \frac{1}{4\pi}\int_{S_e}\upsilon(P')\frac{\partial}{\partial n_{P'}}\frac{1}{|P-P'|}d\sigma(P') \quad (5)$$

A further aspect of the present invention relates to a system for determining a table of sur-

face charge densities or dipole densities of a given heart chamber, comprising :

a) one unit for measuring and recording at least one electric potential V_e at a given position P on the surface of a given heart chamber,

b) one a/d-converter for converting the measured electric potentials into digital data,

c) one memory to save the measured and/or transformed data,

d) one processor unit for transforming the digital voltage data into digital surface charge density data.

Preferably, the unit for measuring and recording the electric potential V comprises electrodes, which are in contact with at least one part of the heart chamber.

Equally preferred is that the unit for measuring and recording the electric potential V_e comprises electrodes, which are not in contact with at least one part of the heart chamber.

Preferably, the system of the invention comprises a unit for representing the surface charge densities $\rho(P, t)$ and/or dipole densities $\nu(P, t)$ as a 2-dimensional picture or time-dependent sequence of pictures (film).

It is also preferred the system of the invention comprises a unit for representing the surface charge densities $\rho(P, t)$ and/or dipole densities $\nu(P, t)$ as a 3-dimensional picture or time-dependent sequence of pictures (film).

In a preferred embodiment, the system of the invention is capable of implementing the above cited methods of the invention.

In a further aspect, the present invention is directed to a computer program comprising instructions for implementing a method of the present invention.

Preferably, the computer program of the invention comprises instructions implementing a system of the invention.

It is also preferred that the computer program of the present invention comprises a computer readable programming-code, starting program after booting a computer and/or a system of the invention to use a method of the invention.

A further aspect of the invention relates to a device for implementing a method according to the invention, comprising at least one an electrode for measuring the electrode potential V_e using the method of contact mapping and/or using the method of non-contact mapping, at least one processing unit for generating and transforming V_e into said surface charge density $\rho(P, t)$ and/or dipole density $\nu(P, t)$ for presenting on a display.

Alternatively, the method of the present invention may be described as a method for determining a database table of surface charge densities of at least one given heart chamber, the surface charge density information comprising at least one triple (data values) (W(P,t,L), wherein

i) P defines the position P(x,y,z) in x, y and z-coordinates of a given surface charge density of the at least one heart chamber,

ii) t is the time of measurement for said surface charge density, and

iii) L is the surface charge density at said time t and said position P derived from a measured electric potential of cardiac cells from a given heart chamber,

comprising the following steps:

a) measuring and/or calculating one or more electric potential(s) V_e of cardiac cells in one or more position(s) P(x,y,z) at the cardiac wall of at least one given heart chamber at a given time t,

b) generating at least one triple W(P,t, V_e) for each given time, position and potential,

c) transforming at least one triple W(P,t, V_e) into said triple W(P,t,L) using an algorithm method suitable for transforming an electric potential into surface charge density.

Also, the method of the present invention may be described as a method for determining a database table of dipole densities of at least one given heart chamber, the dipole density information comprising at least one triple (data values) (W(P,t,D), wherein

i) P defines the position P(x,y,z) in x, y and z-coordinates of a given surface charge density of the at least one heart chamber,

ii) t is the time of measurement for said dipole density, and

iii) D is the dipole density at said time t and said position P derived from a measured electric potential of cardiac cells from a given heart chamber,

comprising the following steps:

a) measuring and/or calculating one or more electric potential(s) V_e of cardiac cells in one or more position(s) P(x,y,z) at the cardiac wall of at least one given heart chamber at a given time t,

b) generating at least one triple $W(P,t,V_e)$ for each given time, position and potential,

c) transforming at least one triple $W(P,t,V_e)$ into said triple W(P,t,D) using an algorithm method suitable for transforming an electric potential into dipole density.

The other aspects and embodiments described above may also be applied analogously the directly above mentioned alternatives.

In another aspect, the present invention provides a method for generating a database table of surface charge densities (ρ) of at least one given heart chamber, the surface charge density information comprising a table $\rho(P, t)$ wherein

i) the position P=(x,y,z) of a point at a cardiac wall of the heart is defined in x, y, z-coordinates,

ii) t is the time of measurement for said surface charge density, and

iii) ρ is the surface charge density at said time t and said position P derived from a measured electric potential from a given heart chamber,

the method comprising the following steps:

a) determining one or more electric potential V_e at one or more position P at the cardiac wall at a given time t, and

b) transforming the one or more electric potential V_e into said charge density $\rho(P,t)$.

In another aspect, the present invention provides a method for generating a database table of dipole densities $\nu(P,t)$ of at least one given heart chamber, the dipole density information comprising a table $\nu(P, t)$, wherein

i) the position P=(x,y,z) of a point at a cardiac wall of the heart is defined in x, y, z-coordinates,

ii) t is the time of measurement for said dipole density, and

iii) ν is the dipole density at said time t and said position P derived from a measured electric potential from a given heart chamber,

the method comprising the following steps:

a) determining one or more electric potential V_e at one or more position P at the cardiac wall at a given time t, and

b) transforming the one or more electric potential V_e into said dipole density $\nu(P,t)$.

In another aspect, the present invention provides a system that generates a table of surface charge densities or dipole densities of a given heart chamber, comprising:

a) a measuring and recording unit that measures and records data used to determine at least one electric potential V_e at a given position P on the surface of a given heart chamber,

b) an a/d-converter that converts the at least one electric potentials V_e into digital voltage data,

c) a processor that transforms the digital voltage data into digital surface charge density data,

d) a memory that stores one or more of the at least one electric potential V_e and the transformed data.

In another aspect, the present invention provides a computer program product stored in a memory and configured to, when executed by at least one processor, perform a method for generating a database table of surface charge densities (ρ) of at least one given heart chamber, the surface charge density information comprising a table $\rho(P, t)$ wherein

i) the position P=(x,y,z) of a point at the wall of the heart is defined in x, y, z-coordinates,

ii) t is the time of measurement for said surface charge density, and

iii) ρ is the surface charge density at said time t and said position P derived from an electric potential from a given heart chamber,

the method comprising the following steps:

a) determining one or more electric potential V_e in one or more position P at the cardiac wall at a given time t, and

b) transforming the one or more electric potential V_e into said charge density $\rho(P,t)$.

In another aspect, the present invention provides a computer program product stored in a memory and configured to, when executed by at least one processor, perform a method for generating a database table of dipole densities $\nu(P,t)$ of at least one given heart chamber, the dipole density information comprising a table $\nu(P, t)$, wherein

i) the position P=(x,y,z) of a point at the wall of the heart is defined in x, y, z-coordinates,

ii) t is the time of measurement for said dipole density, and

iii) ν is the dipole density at said time t and said position P derived from a measured electric potential from a given heart chamber,

the method comprising the following steps:

a) determining one or more electric potential V_e in one or more position P at the cardiac wall at a given time t, and

b) transforming the one or more electric potential V_e into said dipole density $\nu(P,t)$.

In a typical but non-limiting embodiment, the measured and/or calculated potential V_e will be recorded in a database in the form of a table. For generating the triple W(P, t, V_e) is the position P and the time of measurement t will be used. This triple W(P,t,V_e) is the basis for generating a 2 or 3-dimensional map of the surface charge density and/or the dipol density. Therefore, the triple W(P,t,V_e), comprising the values and data of measurement or

preliminary calculations is transformed into another triple comprising the surface charge and/or dipol charge. In a preferred embodiment, the triple W(P,t,V_e) (e.g. after storing) can be used to be transformed into a triple W(P,t,L) and/or a triple W(P,t,D) and/or a triple W(P,t,LD), wherein LD comprises the information of the surface charge and the dipole charge at position P at time t. The process and method for the transformation is preferably based on an algorithm based on formula 4 and/or 5 and/or a BEM-algorithm for the discretisation of the wall of a heart chamber.

Research has indicated that the use of the surface charge densities (i.e. their distribution) or

dipole densities (i.e. their distribution) to generate distribution map(s) will lead to a more detailed and precise information on electric ionic activity of local cardiac cells than potentials. Surface charge density or dipole densities represent a precise and

sharp information of the electric activity with a good spatial resolution, whereas potentials resulting from integration of charge densities provide only a diffuse picture of electric activiy. The electric nature of cardiac cell membranes comprising ionic charges of proteins and soluble ions can be precisely described by surface charge and dipole densities. The surface charge densities or dipole densities cannot be directly measured in the heart, but instead must be mathe-

the method comprising the following steps:

a) determining one or more electric potential V_e at one or more position P at the cardiac wall at a given time t, and

b) transforming the one or more electric potential V_e into said dipole density $\nu(P,t)$.

In another aspect, the present invention provides a system that generates a table of surface charge densities or dipole densities of a given heart chamber, comprising:

a) a measuring and recording unit that measures and records data used to determine at least one electric potential V_e at a given position P on the surface of a given heart chamber,

b) an a/d-converter that converts the at least one electric potentials V_e into digital voltage data,

c) a processor that transforms the digital voltage data into digital surface charge density data,

d) a memory that stores one or more of the at least one electric potential V_e and the transformed data.

In another aspect, the present invention provides a computer program product stored in a memory and configured to, when executed by at least one processor, perform a method for generating a database table of surface charge densities (ρ) of at least one given heart chamber, the surface charge density information comprising a table $\rho(P, t)$ wherein

i) the position P=(x,y,z) of a point at the wall of the heart is defined in x, y, z-coordinates,

ii) t is the time of measurement for said surface charge density, and

iii) ρ is the surface charge density at said time t and said position P derived from an electric potential from a given heart chamber,

the method comprising the following steps:

a) determining one or more electric potential V_e in one or more position P at the cardiac wall at a given time t, and

b) transforming the one or more electric potential V_e into said charge density $\rho(P,t)$.

In another aspect, the present invention provides a computer program product stored in a memory and configured to, when executed by at least one processor, perform a method for generating a database table of dipole densities *v*(P,t) of at least one given heart chamber, the dipole density information comprising a table *v*(P,t), wherein

i) the position P=(x, y, z) of a point at the wall of the heart is defined in x, y, z-coordinates,

ii) t is the time of measurement for said dipole density, and

iii) *v* is the dipole density at said time t and said position P derived from a measured electric potential from a given heart chamber,

the method comprising the following steps:

a) determining one or more electric potential V_e in one or more position P at the cardiac wall at a given time t, and

b) transforming the one or more electric potential V_e into said dipole density *v*(P,t).

In another aspect, the present invention provides a method for generating a database table of surface charge densities (ρ) that embody an ionic nature of cellular membranes across an endocardium of at least one given heart chamber, the cellular membrane surface charge density information comprising a table ρ(P', t) wherein: i) a position P'=(x',y',z') of a point on the cellular membrane of the endocardial wall in a heart chamber is defined in x, y, z-coordinates, ii) t is a time of measurement for said cellular membrane surface charge density, and iii) ρ is the cellular membrane surface charge density at said time t and said position P' derived from a measured electric potential from the heart chamber, the method comprising the following steps: a) determining electric potential data V_e at locations P in the heart chamber at a given time t using a probe electrode of a mapping system, b) transforming the electric potential data V_e into said cellular membrane surface charge density ρ(P',t) at positions P' on the endocardial wall using a processor executing a set of conversion instructions stored in a computer memory, and c) storing each cellular membrane surface charge density in the computer memory as a table of cellular membrane surface charge densities.

In yet another aspect, the present invention provides a method for generating a database table of dipole densities v(P',t) that embody an ionic nature of cellular membranes across an endocardium of at least one given heart chamber, the

dipole density information comprising a table v(P', t), wherein: i) a position P'=(x',y',z') of a point on the cellular membrane of the endocardial wall of the heart chamber is defined in x, y, z-coordinates, ii) t is a time of measurement for said cellular membrane dipole density, and iii) v is the cellular membrane dipole density at said time t and said position P' derived from a measured electric potential from the heart chamber, the method comprising the following steps: a) determining electric potential data V_e at locations P in the heart chamber at a given time t using a probe electrode of a mapping system, b) transforming the electric potential data V_e into said cellular membrane dipole density v(P',t) at positions P' on the endocardial wall using a processor executing a set of conversion instructions stored in a computer memory, and c) storing each dipole density in the computer memory as a table of cellular membrane dipole densities.

In yet a further aspect, the present invention provides a system that generates a table of surface charge densities ρ(P', t) that embody an ionic nature of cellular membranes across the endocardium of a given heart chamber, comprising: a) a measuring and recording unit that measures and records electric potential data V_e at given positions P in the heart chamber, b) an a/d-converter that converts the electric potential data V_e into digital voltage data, c) a processor that transforms the digital voltage data into digital cellular membrane surface charge density data, and d) a memory that stores the electric potential data V_e and the transformed digital cellular membrane surface charge density data.

Brief Description of the Drawings

Fig. 1 is an exemplary embodiment of a mapping system, according to an aspect of the present invention;

Fig. 2 is an exemplary embodiment of a computer architecture forming part of the mapping system of Fig. 1;

Fig. 3 is a flow chart outlining steps of a method of determining and storing surface charge densities, in accordance with aspects of the present invention; and

Fig. 4 is a flow chart outlining steps of a method of determining and storing dipole densities, in accordance with aspects of the present invention.

Detailed Description of the Preferred Embodiments

In a typical but non-limiting embodiment, the measured and/or calculated potential V_e will be recorded in a database in the form of a table. For generating the triple W(P,t, V_e) is the position P and the time of measurement t will be used. This triple W(P,t,V_e) is the basis for generating a 2 or 3-dimensional map of the surface charge density and/or the dipol density. Therefore, the triple W(P,t,V_e), comprising the values and data of measurement or preliminary calculations is transformed into another triple comprising the surface charge and/or dipol charge. In a preferred embodiment, the triple W(P,t,V_e) (e.g. after storing) can be used to be transformed into a triple W(P,t,L) and/or a triple W(P,t,D) and/or a triple W(P,t,LD), wherein LD comprises the information of the surface charge and the dipole charge at position P at time t. The process and method for the transformation is preferably based on an algorithm based on formula 4 and/or 5 and/or a BEM-algorithm for the discretisation of the wall of a heart chamber.

Research has indicated that the use of the surface charge densities (i.e. their distribution) or dipole densities (i.e. their distribution) to generate distribution map(s) will lead to a more detailed and precise information on electric ionic activity of local cardiac cells than potentials. Surface charge density or dipole densities represent a precise and sharp information of the electric activity with a good spatial resolution, whereas potentials resulting from integration of charge densities provide only a diffuse picture of electric activiy. The electric nature of cardiac cell membranes comprising ionic charges of proteins and soluble ions can be precisely described by surface charge and dipole densities. The surface charge densities or dipole densities cannot be directly measured in the heart, but instead must be mathematically and accurately calculated starting from measured potentials. In other words, the information of voltage maps obtained by current mapping systems can be greatly refined when calculating surface charge densities or dipole densities from these.

The surface charge density means surface charge (Coulombs) per unit area (cm^2). A dipol as such is a neutral element, wherein a part comprises a positive charge and the other part comprises the same but negative charge. A dipol might represent the electric nature of cellular membranes better, because in biological environment ion charges are not macroscopically separated.

In order to generate a map of surface charge densities (surface charge density distribution) according to the present invention, the geometry of the given heart chamber must be known. The 3D geometry of the cardiac chamber is typically assessed by currently available and common mapping systems (so-called locator systems) or, alternatively, by integrating anatomical data from CT/MRI scans. Fig. 1 shows an exemplary embodiment of a mapping system 100 that can be used to map a heart 12 of a human 10. Mapping system 100 can include a computer having known types of input devices and output devices, and a probe system 140. For the measurement of potentials the non-contact mapping method a probe electrode 142 will be used which forms part of probe system 140.

The probe electrode 142 may be a multielectrode array with elliptic or spherical shape. The spherical shape has certain advantages for the subsequent data analysis. For example, when considering, for example, the ventricular cavity with the endocardium and take a probe electrode 142 with a surface S_p, which is located in the blood, it is possible to measure the potential V(x,y,z) at point x,y,z on the surface S_p. In order to calculate the potential at the endocardial surface S_e the Laplace equation

$$\Delta V = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)V = 0 \quad (1)$$

needs to be solved, wherein V is the potential and x,y,z denote the three dimensional coordinates. The boundary conditions for this equation are $V(x,y,z)=V_p(x,y,z)$ on S_p, wherein V_p is the potential on surface of the probe 142.

The solution is an integral that allows for calculating the potential V(x'y'z') at any point x'y'z' in the whole volume of the heart chamber that is filled with blood. For calculating said integral numerically a discretisation of the cardiac surface is necessary and the so called boundary element method (BEM) has to be used.

The boundary element method is a numerical computational method for solving linear integral equations (i.e. in surface integral form). The method is applied in many areas of engineering and science including fluid mechanics, acoustics, electromagnetics, and fracture mechanics.

The boundary element method is often more efficient than other methods, including the finite element method. Boundary element formulations typically give rise to fully populated matrices after discretisation. This means, that the storage requirements and computational time will tend to grow according to the square of the problem size. By contrast, finite element matrices are typically banded (elements are only locally connected) and the storage requirements for the system matrices typically grow quite linearly with the problem size.

With the above in mind, all potentials V_P (x1'y1'z1') on the surface of the probe 142 can be measured . To calculate the potential V_e on the wall of the heart chamber, the known geometry of the surface of the heart chamber must be divided in discret parts to use the boundary element method . The endocardial potentials V_e are then given by a linear matrix transformation T from the probe potentials V_P : $V_e = T\ V_P$.

After measuring and calculating one or more electric potential(s) V_e of cardiac cells in one or more position(s) P(x,y,z) of the at least one given heart chamber at a given time t . The surface charge density and the dipol density is related to potential according to the following two Poisson equations:

$$\Delta V_e = \rho(P)\delta_{S_e}(P) \quad (2)$$

$$\Delta V_e = \frac{\delta}{\partial n}(\upsilon\delta_{S_e}(P)) \quad (3)$$

wherein $\rho(P)$ is the surface charge density in position P=x,y,z, $\delta_{S_e}(P)$ is the delta-distribution concentrated on the surface of the heart chamber S_e and υ is the dipol density.

There is a well known relationship between the potential V_e on the surface of the wall of the heart chamber and the surface charge (4) or dipole densities (5).

$$V_e(P) = -\frac{1}{4\pi}\int_{S_e}\frac{\rho(P')}{|P'-P|}d\sigma(P') \quad (4)$$

$$V_e(P) = \frac{1}{4\pi}\int_{S_e}\upsilon(P')\frac{\partial}{\partial n_{P'}}\frac{1}{|P-P'|}d\sigma(P') \quad (5)$$

(For a review see Jackson JD. Classical Electrodynamics, 2nd edition, Wiley, New York 1975.)

The boundary element method again provides a code for transforming the potential V_e in formula 4 and 5 into the desired surface charge densities and dipole densities , which can be recorded in the database

In another embodiment of the method of the present invention the electric potential(s) V_e is (are) determined by contact mapping. In this case the steps for calculating the electric potential V_e are not necessary, because the direct contact of the electrode 142 to the wall of the heart chamber already provides the electric potential V_e.

In a preferred embodiment of the method of the present invention the probe electrode 142 comprises a shape that allows for calculating precisely the electric potential V_e and, thus, simplifies the calculations for transforming V_e into the desired charge or dipole densities. This preferred geometry of the electrode 142 is essentially ellipsoidal or spherical.

In order to employ the method for determining a database table of surface charge densities of at least one given heart chamber in the context of the present invention, it is preferred to use a system comprising at least:

a) one unit for measuring and recording electric potentials V at a given position P(x,y,z) on the surface of a given heart chamber (Contact mapping) or a probe electrode 142 positioned within the heart 12, but without direct wall contact (non-contact mapping)

b) one a/d-converter for converting the measured electric potentials into digital data,

c) one memory to save the measured and/or transformed data,

d) one processor unit for transforming the digital data into digital surface charge density or dipole density data.

It is noted that numerous devices for localising and determining electric potentials of cardiac cells in a given heart chamber by invasive and non-invasive methods are well known in the art and have been employed by medical practitioners over many years. Hence, the method, system, and devices of the present invention do not require any particular new electrodes 142 for implementing the best mode for practicing the present invention. Instead, the invention provides a new and advantageous processing of the available data that will allow for an increase in precision, accuracy and spatial resolution of cardiac activation mapping when compared to prior art systems based on electric surface potentials in the heart 12 only. In the near future, the present invention will allow for providing superior diagnostic means for diagnosing cardiac arrhythmias and electric status of heart cells including metabolic and functional information.

Fig. 2 provides an exemplary embodiment of a computer architecture that can form part of mapping system 100. The mapping system 100 includes an A/D converter for converting measured electric potentials from the probe system 140 into digital data; a processor unit for transforming the digital data into digital surface charge density or dipole density data; and a memory to save the measured and/or transformed data.

Fig. 3 and Fig.4 summarize methods for determining and storing surface charge densities and dipole densities, respectively, in accordance with aspects of the present invention, which have been described in detail above.

In method 300 of Fig. 3, in step 302, mapping system 100 is used to measure and/or calculate one or more electric potential(s) V_e in one or more position(s) P within a heart chamber at a given time t. In step 304, V_e is transferred into a surface charge density p(P',t). In step 306, the surface charge density p(P',t) is stored in a database table. The method is repeated if there is another P, in step 308.

In method 400 of Fig. 4, in step 402, mapping system 100 is used to measure and/or calculate one or more electric potential(s) V_e in one or more positions(s) P within a heart chamber at a given time t. In step 404, V_e is transferred into a dipole density v(P',t) by using an algorithm suitable for transforming an electric potential into surface charge density. In step 406, the dipole density v(P',t) is stored in a database table. The method is repeated if there is another P, in step 408.

We claim:

1. A method for generating a database table of surface charge densities (ρ) that embody an ionic nature of cellular membranes across an endocardium of at least one given heart chamber, the cellular membrane surface charge density information comprising a table ρ(P', t) wherein:

i) a position P'=(x',y',z') of a point on the cellular membrane of the endocardial wall in a heart chamber is defined in x, y, z-coordinates,

ii) t is a time of measurement for said cellular membrane surface charge density, and

iii) ρ is the cellular membrane surface charge density at said time t and said position P' derived from a measured electric potential from the heart chamber,

the method comprising the following steps:

a) determining electric potential data V_e at locations P in the heart chamber at a given time t using a probe electrode of a mapping system,

b) transforming the electric potential data V_e into said cellular membrane surface charge density ρ(P',t) at positions P' on the endocardial wall using a processor executing a set of conversion instructions stored in a computer memory, and

c) storing each cellular membrane surface charge density in the computer memory as a table of cellular membrane surface charge densities.

2. The method according to claim 1, where the electric potential data V_e is determined by contact mapping.

3. The method according to claim 1, wherein the electric potential data V_e is determined by non-contact mapping.

4. The method according to claim 1, wherein transforming the electric potential data V_e into the cellular membrane surface charge density (ρ) in step b) employs a boundary element method (BEM).

5. The method according to claim 1, where a geometry of a probe electrode used in determining the electric potential data V_e is ellipsoidal.

6. The method according to claim 1, where a geometry of the probe electrode used in determining the electric potential data V_e is spherical.

7. The method according to claim 1, wherein said electric potential data V_e is transformed into the cellular membrane surface charge densities ρ using the following equation:

$$V_e(P) = -\frac{1}{4\pi}\int_{S_e}\frac{\rho(P')}{|P'-P|}d\sigma(P')$$

wherein:

S_e=surface of the endocardium;

P'=integration variable running over the entire endocardial wall; and

P=Position of the measuring electrode.

8. A system that generates a table of surface charge densities ρ(P', t) that embody an ionic nature of cellular membranes across the endocardium of a given heart chamber, comprising:

a) a measuring and recording unit that measures and records electric potential data V_e at given positions P in the heart chamber,

b) an a/d-converter that converts the electric potential data V_e into digital voltage data,

c) a processor that transforms the digital voltage data into digital cellular membrane surface charge density data, and

d) a memory that stores the electric potential data V_e and the transformed digital cellular membrane surface charge density data.

9. The system of claim 8, wherein the measuring and recording unit comprises electrodes configured to measure the electric potential data V_e when brought into contact with at least one part of the heart chamber.

10. The system of claim 8, wherein the measuring and recording unit comprises electrodes configured to measure the electric potential data V_e when not in contact with at least one part of the heart chamber.

11. The system of claim 8, further comprising: an imaging unit that represents the cellular membrane surface charge densities ρ(P', t) as a 2-dimensional image or time-dependent sequence of images.

12. The system of claim 8, further comprising: an imaging unit that represents the cellular membrane surface charge densities ρ(P', t) as a 3-dimensional image or time-dependent sequence of images.

13. A computer readable memory having stored thereon a computer program configured to, when executed by at least one processor, perform a method for generating a database table of surface charge densities (ρ) that embody an ionic nature of cellular membranes across the endocardium of at least one given heart chamber, the cellular membrane surface charge density information comprising a table ρ(P', t) wherein:

i) a position P'=(x',y',z') of a point on the cellular membrane of the endocardial wall in a heart chamber is defined in x, y, z-coordinates,

ii) t is a time of measurement for said cellular membrane surface charge density, and

iii) ρ is the cellular membrane surface charge density at said time t and said position P' derived from an electric potential from the heart chamber,

the method comprising the following steps:

a) determining electric potential data V_e at positions P in the heart chamber at a given time t, and

b) transforming the one or more electric potential data V_e into said cellular membrane charge density ρ(P',t).

14. The computer readable memory of claim 13, wherein said electric potential data V_e is transformed into surface charge densities ρ using the following equation:

$$V_e(P) = -\frac{1}{4\pi}\int_{S_e}\frac{\rho(P')}{|P'-P|}d\sigma(P')$$

wherein:

S_e=surface of the endocardium;

P'=integration variable running over the entire endocardial wall; and

P=Position of the measuring electrode.

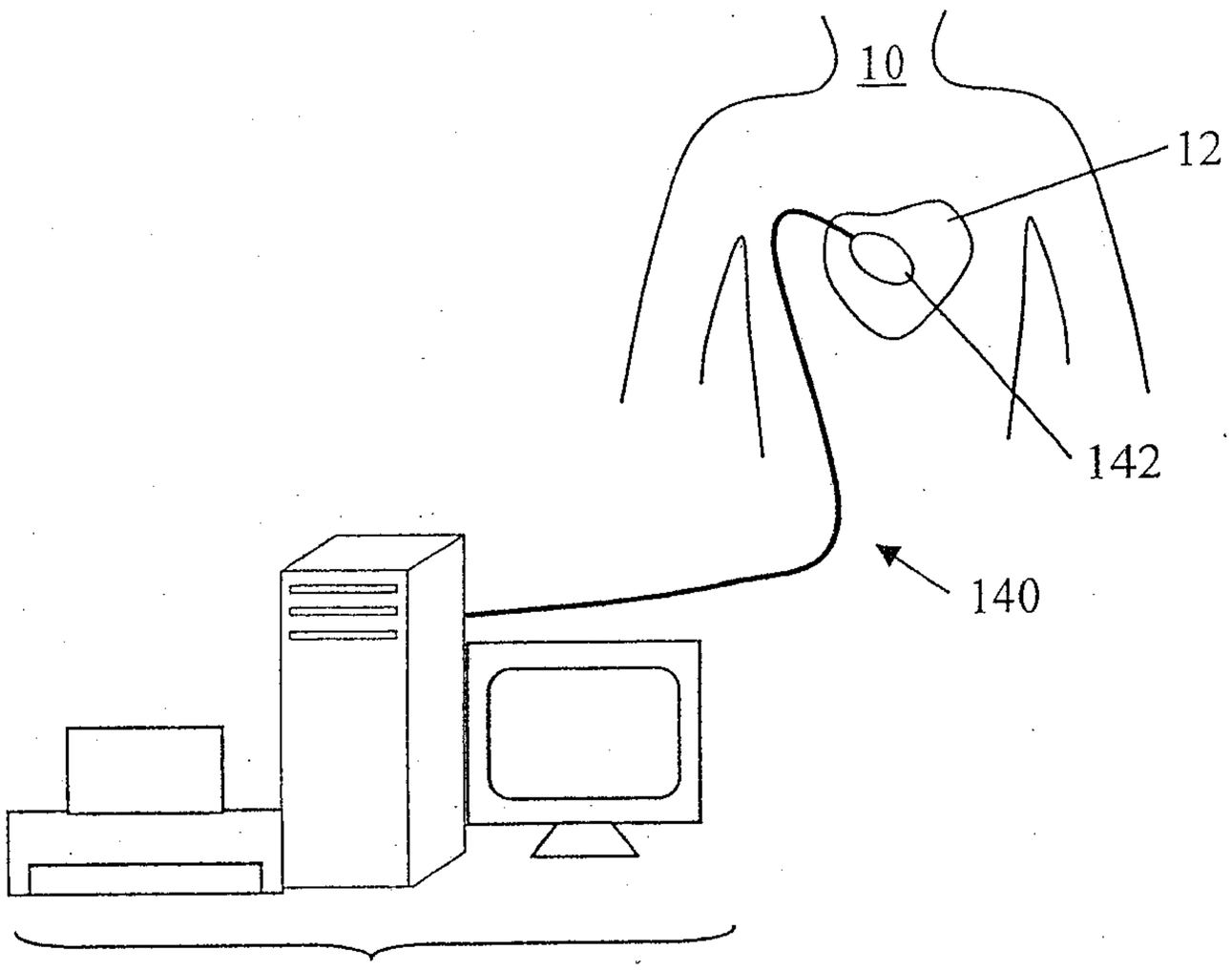


FIG. 1

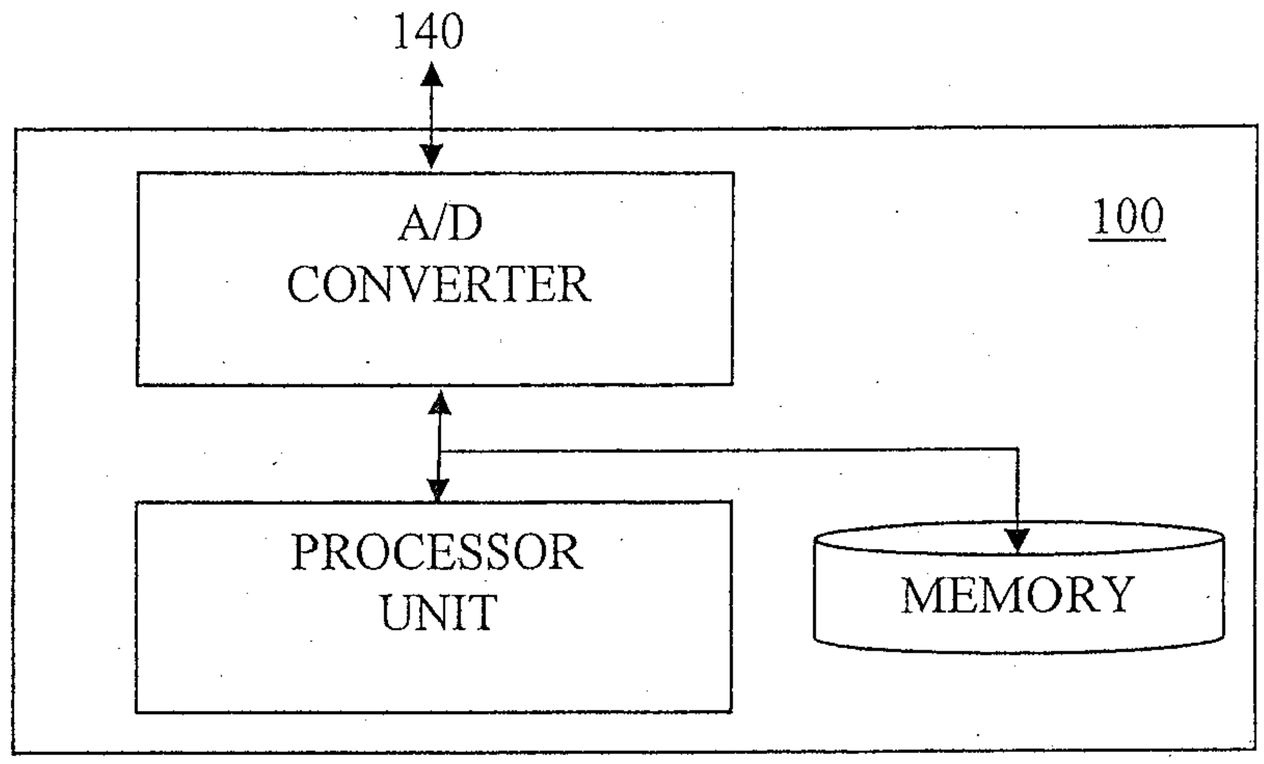


FIG. 2

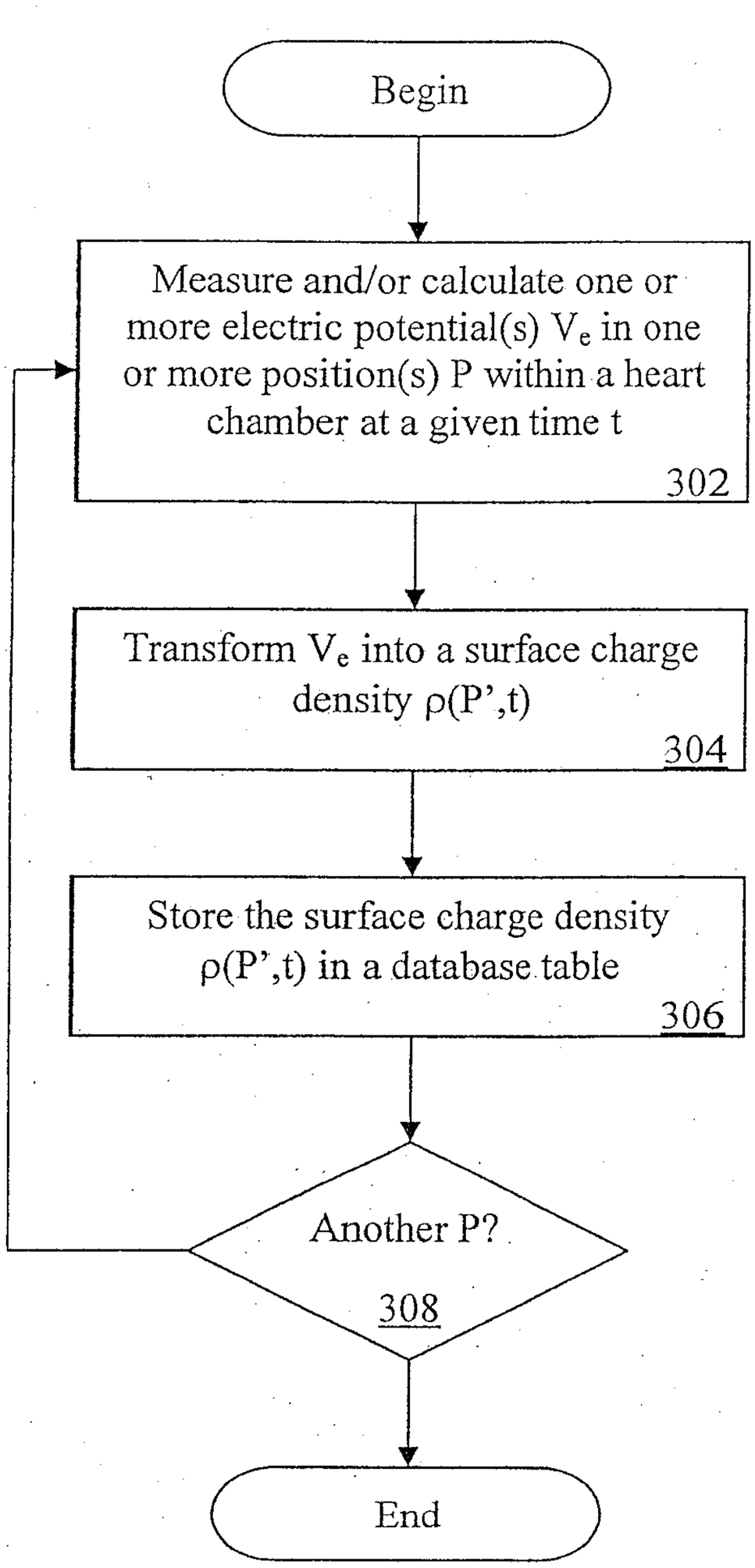

300
Begin
Measure and/or calculate one or more electric potential(s) V_e in one or more position(s) P within a heart chamber at a given time t
302
Transform V_e into a surface charge density $\rho(P',t)$
304
Store the surface charge density $\rho(P',t)$ in a database table
306
Another P?
308
End

FIG. 3

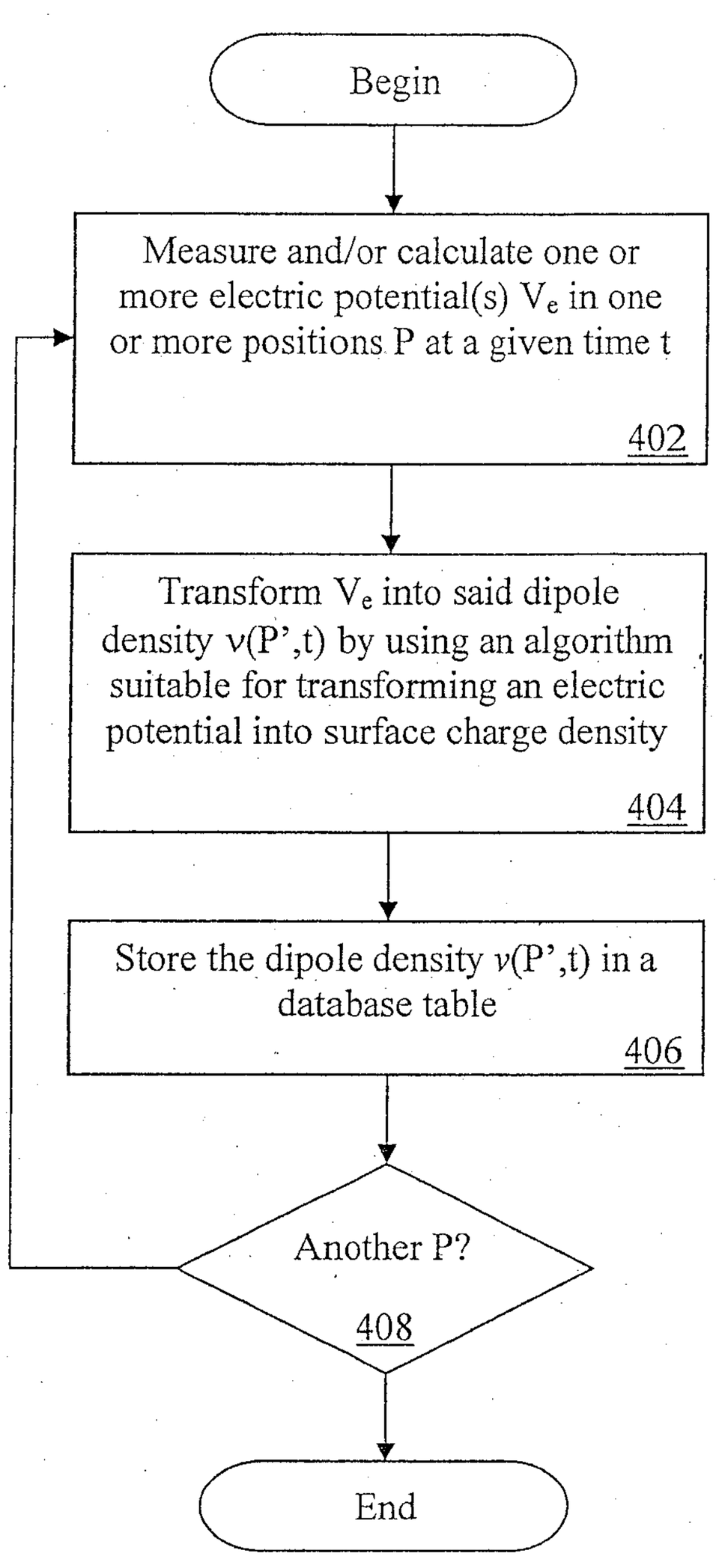
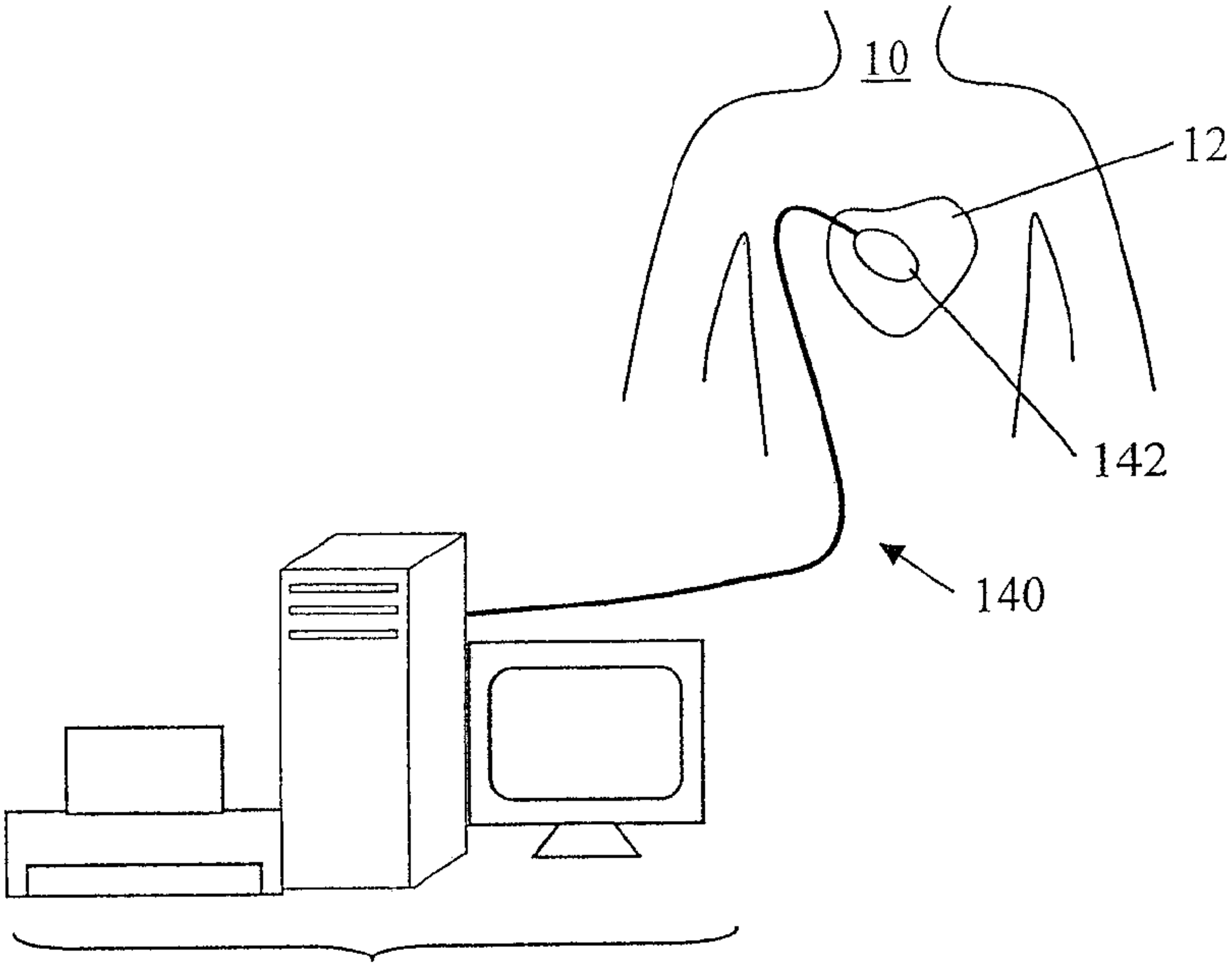

400
Begin
Measure and/or calculate one or more electric potential(s) V_e in one or more positions P at a given time t
402
Transform V_e into said dipole density $\nu(P',t)$ by using an algorithm suitable for transforming an electric potential into surface charge density
404
Store the dipole density $\nu(P',t)$ in a database table
406
Another P?
408
End

FIG. 4


10
12
142
140
100