US 20140303512A1

(19) **United States**
(12) **Patent Application Publication** (10) **Pub. No.: US 2014/0303512 A1**
Patterson et al. (43) **Pub. Date: Oct. 9, 2014**

(54) **MONITOR OF HEART FAILURE USING BIOIMPEDANCE**

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(21) Appl. No.: **14/251,948**

(22) Filed: **Apr. 14, 2014**

Related U.S. Application Data

(63) Continuation of application No. 13/122,664, filed on Jun. 20, 2011, now Pat. No. 8,731,653, filed as application No. PCT/US2009/060223 on Oct. 9, 2009.

(60) Provisional application No. 61/104,631, filed on Oct. 10, 2008.

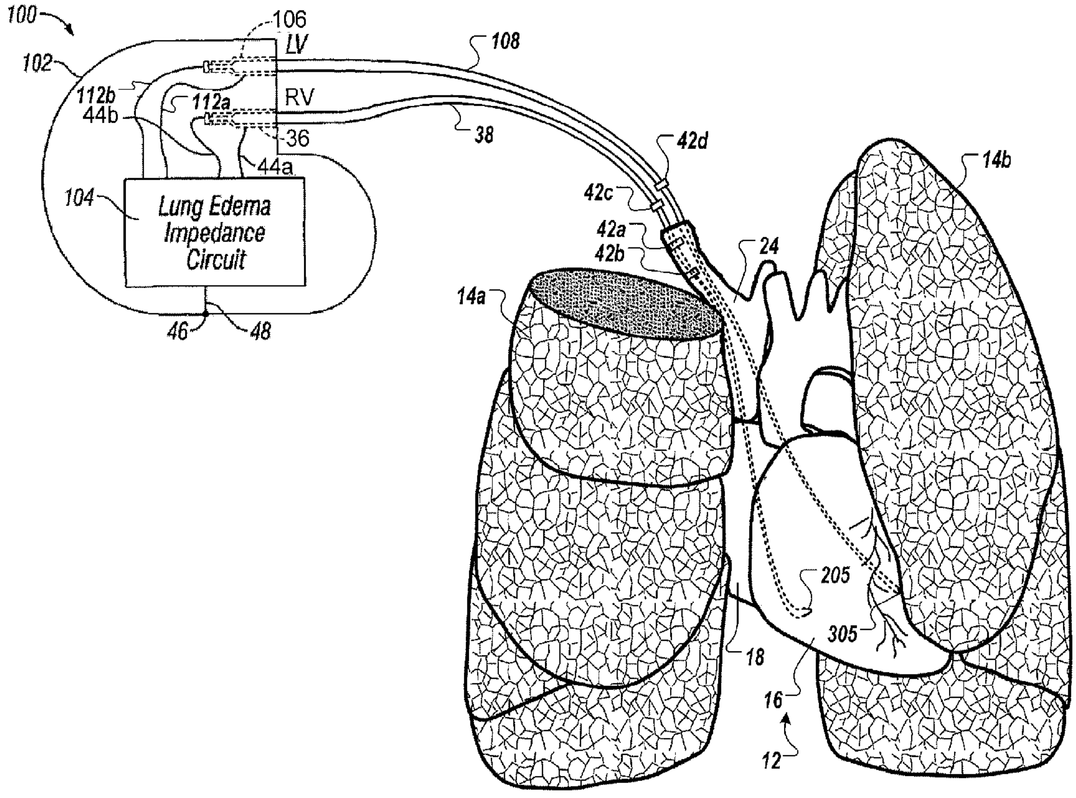
Publication Classification

(51) **Int. Cl.**
A61B 5/00 (2006.01)
A61B 5/053 (2006.01)

(52) **U.S. Cl.**
CPC *A61B 5/4878* (2013.01); *A61B 5/053* (2013.01)
USPC **600/547**

(57) **ABSTRACT**

In a method of monitoring pulmonary edema in a human being, an electrical current is injected between a first electrode located in or around a heart and a housing of a medical device implanted in a chest region. A voltage potential is measured between a second electrode in a superior vena cava and a third electrode in the superior vena cava, where the voltage potential is created by the electrical current. Pulmonary edema is assessed based on an impedance value calculated from the electrical current and the voltage potential and a stored edema threshold impedance value.



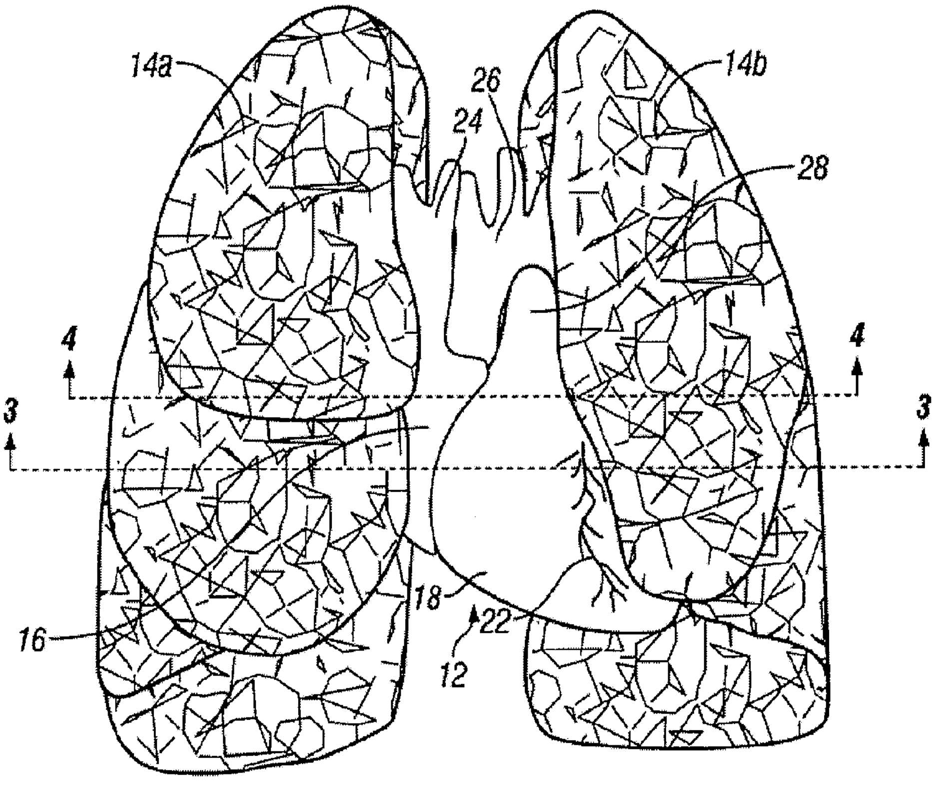


FIG. 1

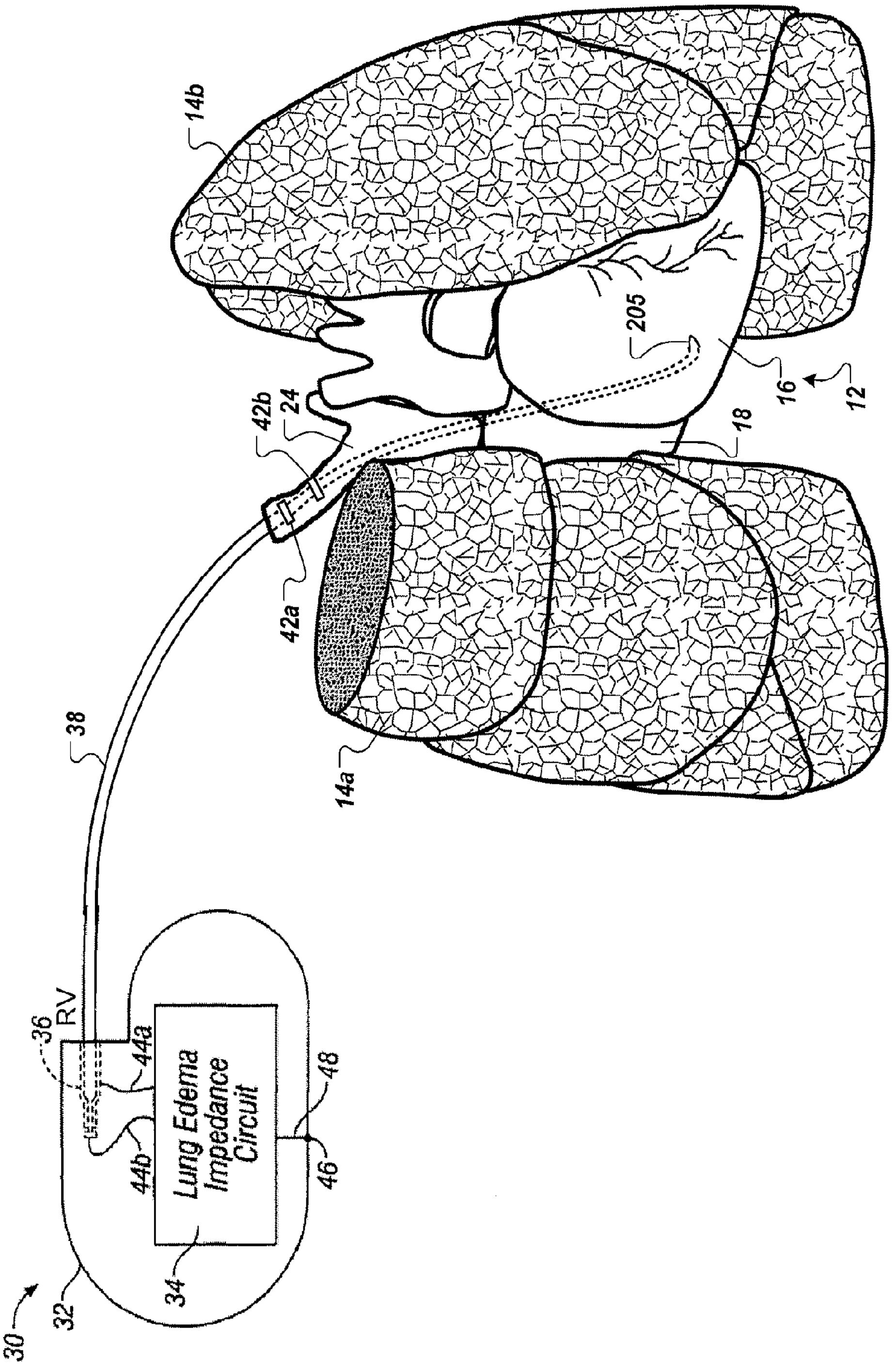

30
32
34
Lung Edema Impedance Circuit
44b
36
RV
44a
46
48
38
42a
42b
24
14a
14b
205
16
12
18

FIG. 2

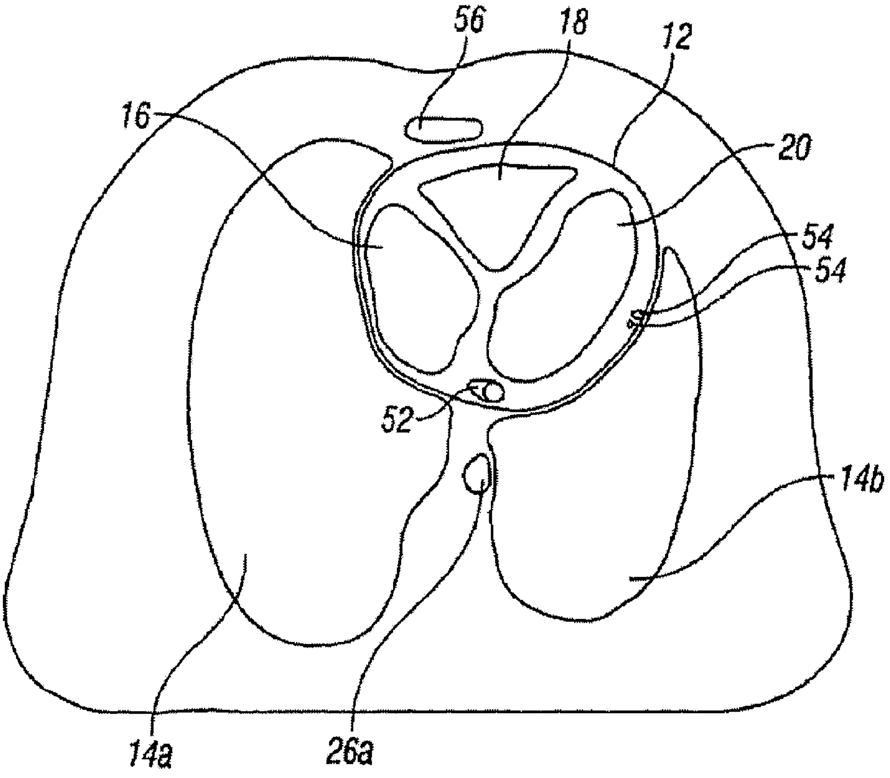


FIG. 3

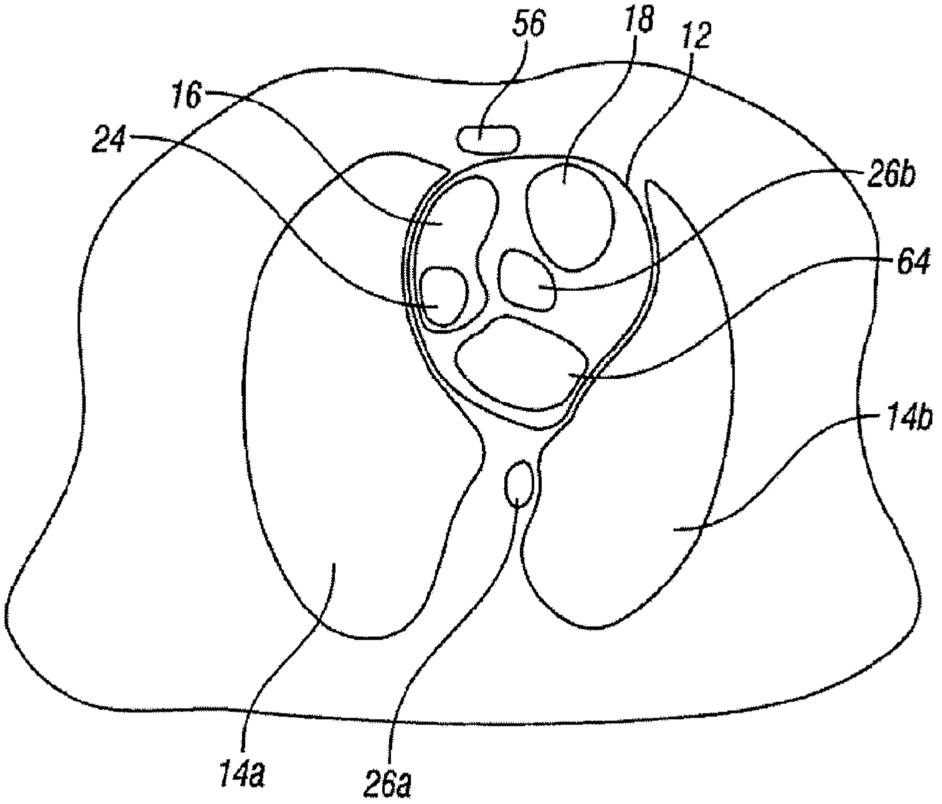


FIG. 4

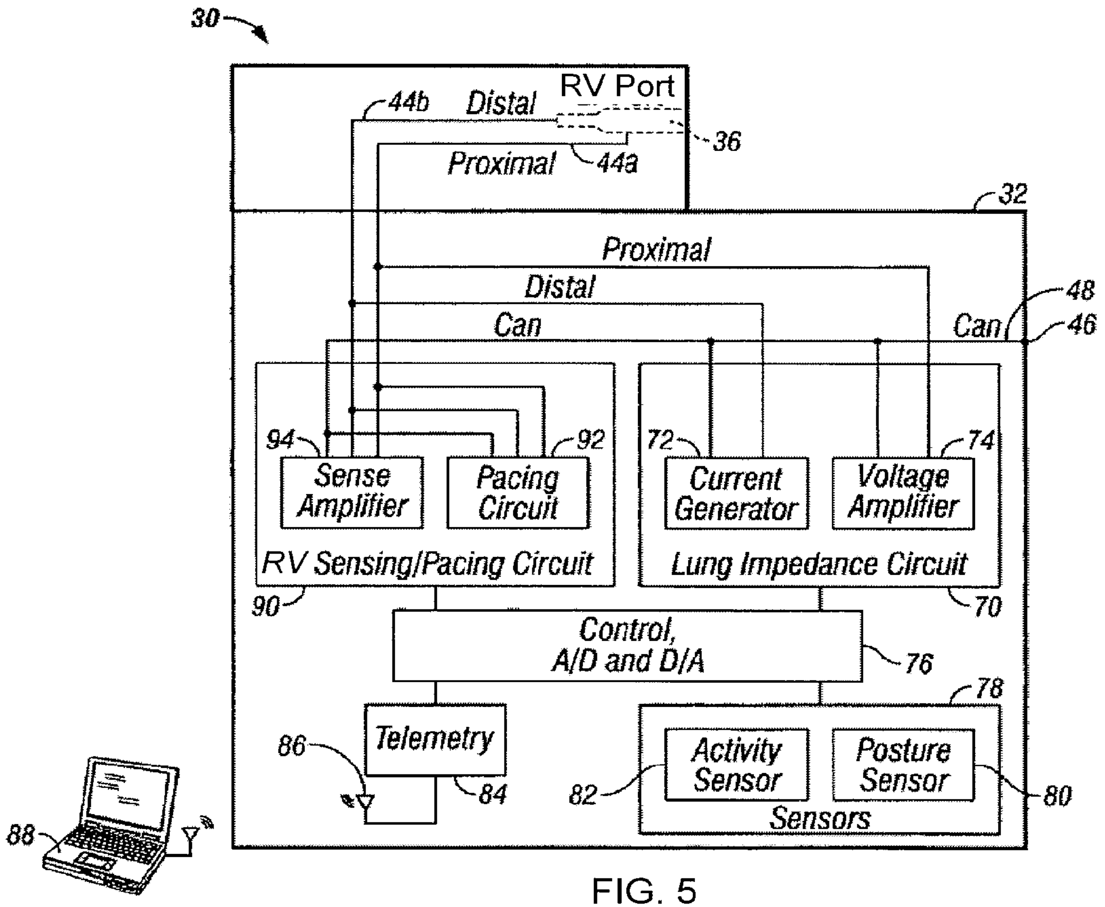

30
RV Port
44b
Distal
36
Proximal
44a
32
Proximal
Distal
Can
Can
48
46
94
Sense Amplifier
Pacing Circuit
92
72
Current Generator
Voltage Amplifier
74
RV Sensing/Pacing Circuit
Lung Impedance Circuit
90
70
Control, A/D and D/A
76
78
Telemetry
86
84
82
Activity Sensor
Posture Sensor
80
Sensors
88

FIG. 5

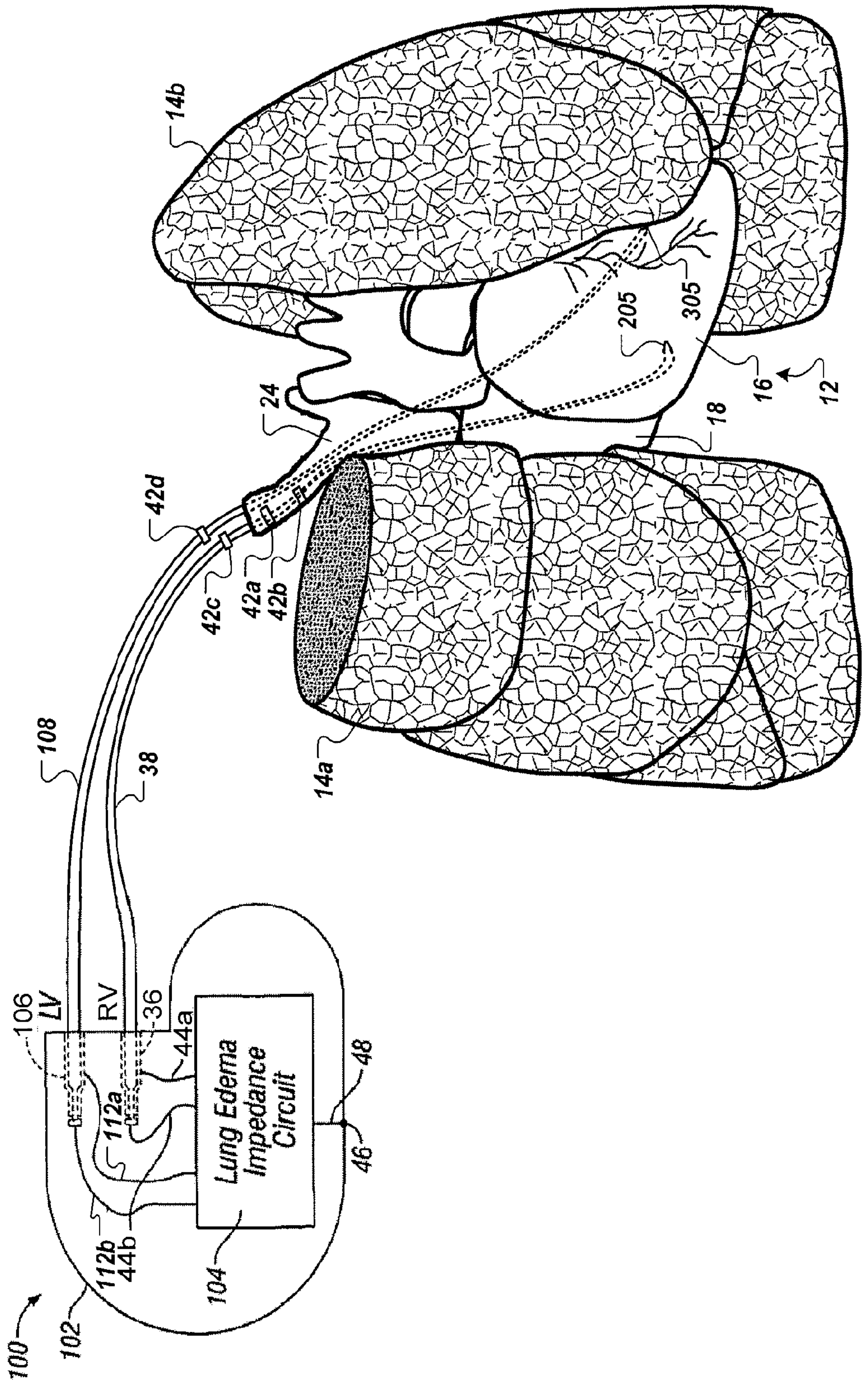

100
102
104
106
LV
RV
36
44a
112a
112b
44b
Lung Edema Impedance Circuit
46
48
108
38
42c
42d
42a
42b
14a
14b
24
18
16
12
205
305

FIG. 6A

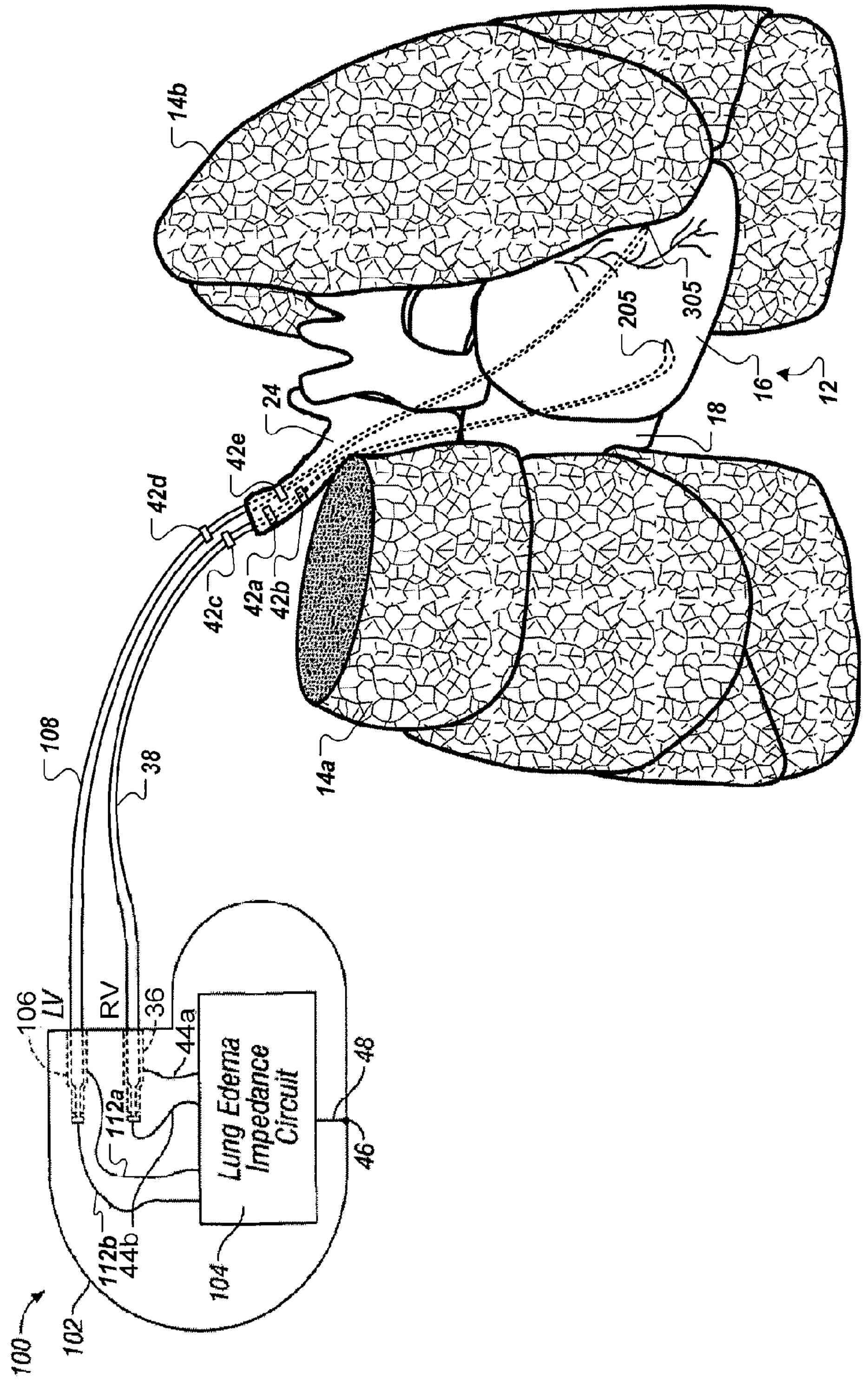

100
102
104
Lung Edema Impedance Circuit
112b
44b
112a
106
LV
RV
36
44a
48
46
108
38
42c
42d
42a
42b
42e
24
14a
14b
18
16
12
205
305

FIG. 6B

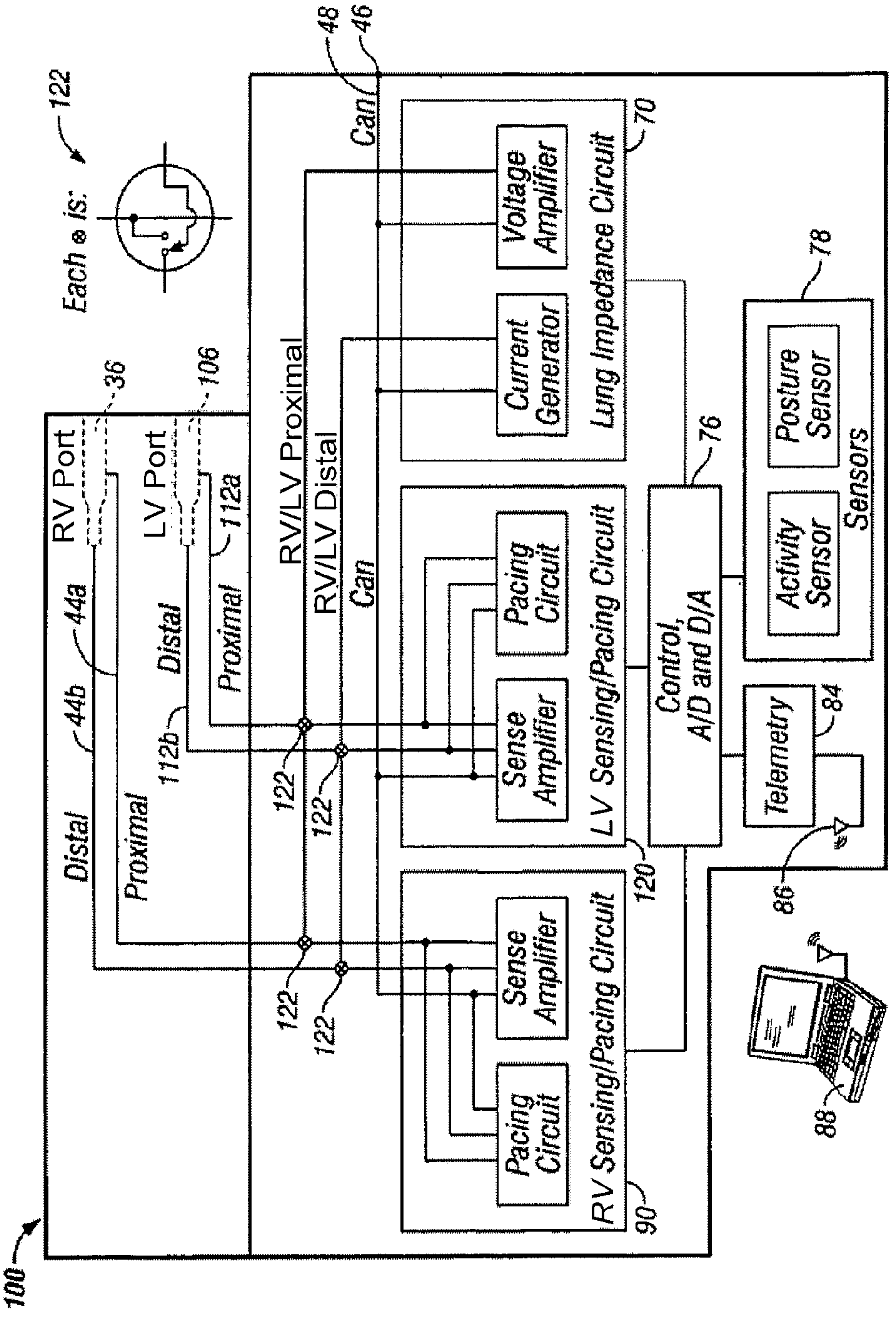

100
Each ⊗ is:
122
RV Port
36
LV Port
106
112a
44a
44b
Distal
Proximal
112b
Distal
Proximal
RV/LV Proximal
RV/LV Distal
Can
Can
48
46
122
122
122
122
Voltage Amplifier
Current Generator
Lung Impedance Circuit
70
Sense Amplifier
Pacing Circuit
LV Sensing/Pacing Circuit
120
Sense Amplifier
Pacing Circuit
RV Sensing/Pacing Circuit
90
Control, A/D and D/A
76
Activity Sensor
Posture Sensor
Sensors
78
Telemetry
84
86
88

FIG. 7

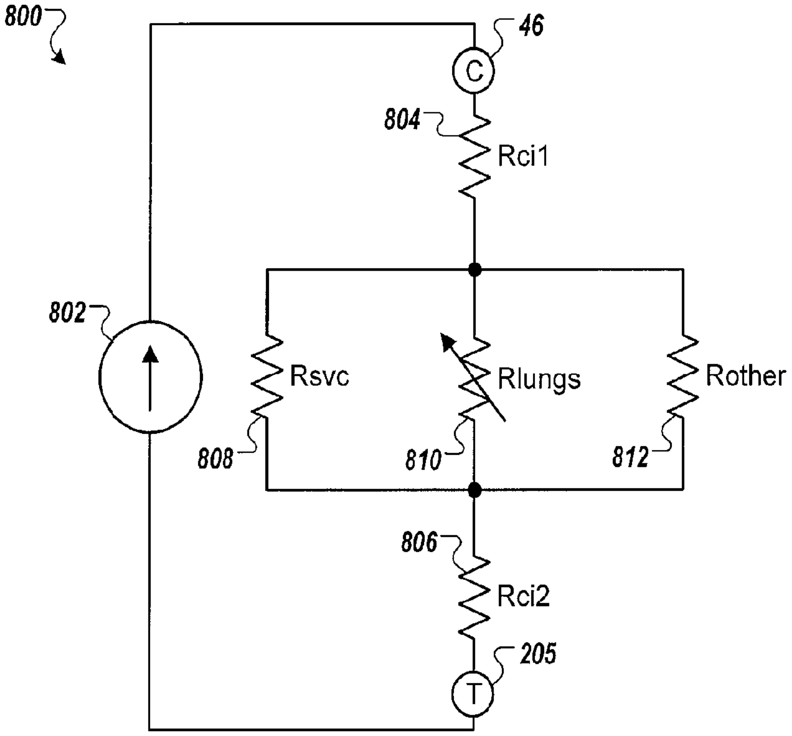

800
46
C
804
Rci1
802
Rsvc
Rlungs
Rother
808
810
812
806
Rci2
205
T

FIG. 8A

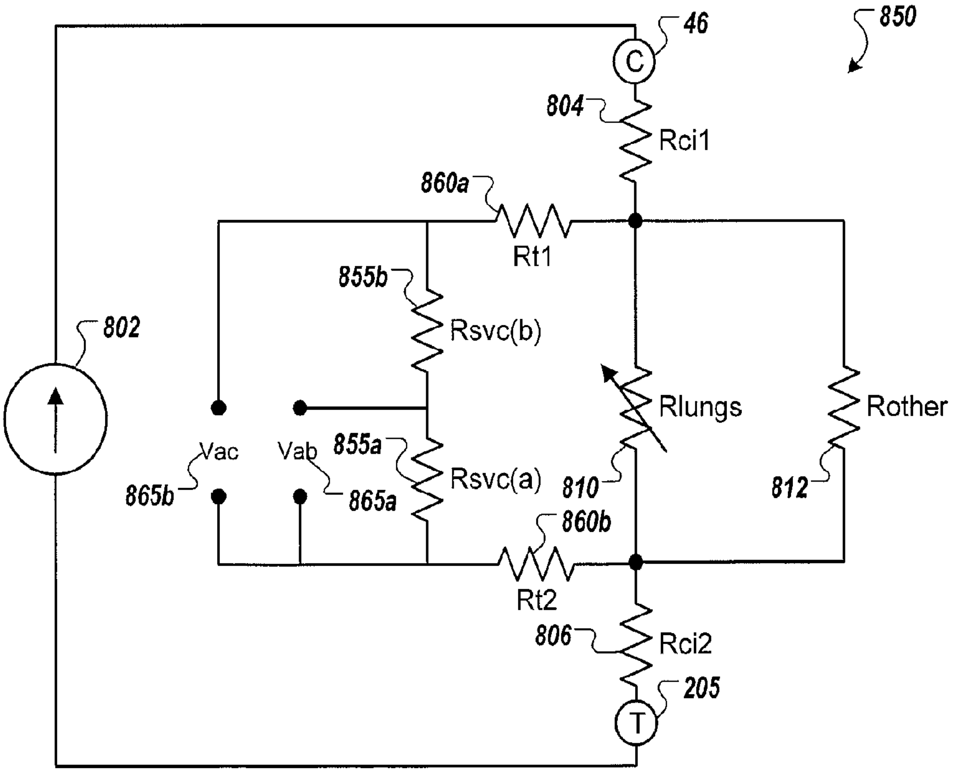

46
850
C
804
Rci1
860a
Rt1
855b
Rsvc(b)
802
Rlungs
Rother
Vac
Vab
855a
Rsvc(a)
865b
865a
810
812
860b
Rt2
806
Rci2
205
T

FIG. 8B

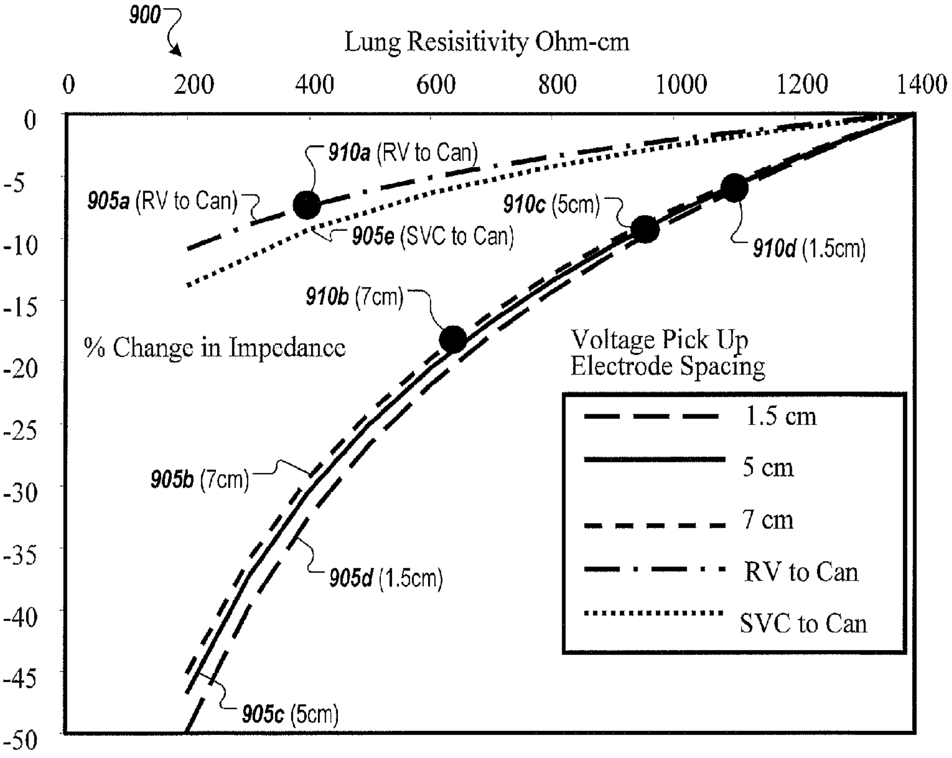

900
Lung Resisitivity Ohm-cm
0
200
400
600
800
1000
1200
1400
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
910a (RV to Can)
905a (RV to Can)
905e (SVC to Can)
910c (5cm)
910d (1.5cm)
910b (7cm)
% Change in Impedance
Voltage Pick Up
Electrode Spacing
1.5 cm
5 cm
7 cm
RV to Can
SVC to Can
905b (7cm)
905d (1.5cm)
905c (5cm)

FIG. 9

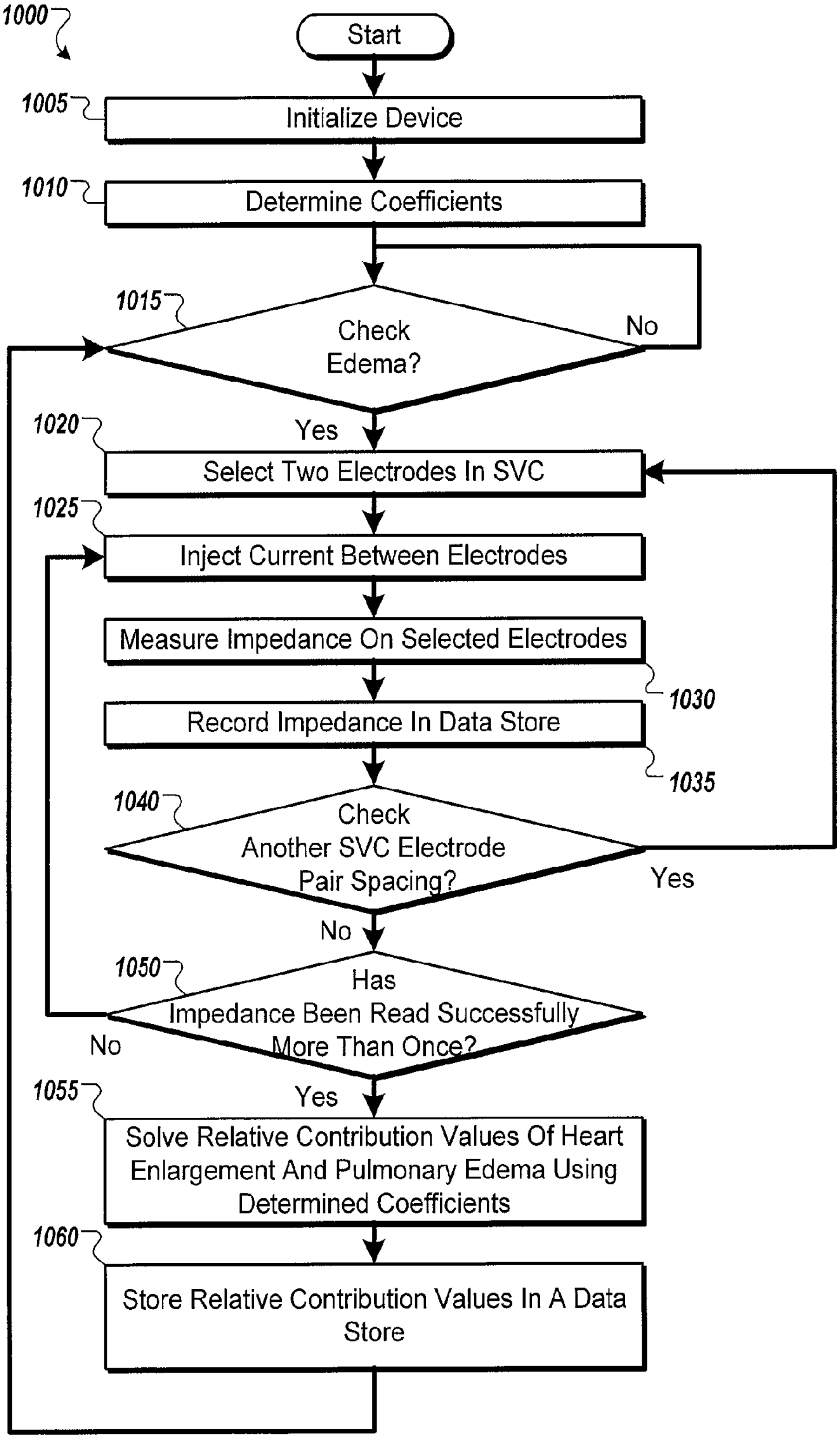

1000
Start
1005
Initialize Device
1010
Determine Coefficients
1015
Check Edema?
No
Yes
1020
Select Two Electrodes In SVC
1025
Inject Current Between Electrodes
Measure Impedance On Selected Electrodes
1030
Record Impedance In Data Store
1035
1040
Check Another SVC Electrode Pair Spacing?
Yes
No
1050
Has Impedance Been Read Successfully More Than Once?
No
Yes
1055
Solve Relative Contribution Values Of Heart Enlargement And Pulmonary Edema Using Determined Coefficients
1060
Store Relative Contribution Values In A Data Store

FIG. 10

MONITOR OF HEART FAILURE USING BIOIMPEDANCE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Application Ser. No. 61/104,631, filed on Oct. 10, 2008, and entitled "Improved Monitor Of Heart Failure Using Bioimpedance," the entire contents of which are incorporated herein by reference.

TECHNICAL FIELD

[0002] The description relates to impedance monitoring in a living being for the detection of pulmonary edema and thoracic congestion.

BACKGROUND

[0003] Pulmonary edema is a serious medical condition caused by an excess accumulation of fluid within a patient's lungs. Pulmonary edema can be an indicator of cardiac-related diseases, such as congestive heart failure. Good management of pulmonary edema is desirable because it may allow timely therapeutic interventions, and avoid hospitalization and its costs.

[0004] It is possible to detect fluid in the lungs by making an electrical impedance measurement across the lungs. The more fluid there is in the lungs, the lower the impedance. One known way this may be done is by using an implantable medical device such as a pacemaker or defibrillator implanted in the chest area of the patient. An electrical impedance measurement is conventionally made between right ventricular chamber electrodes connected to the implanted device, and another electrode at the implanted device itself; thus, the impedance measurement samples thoracic tissues, including the lungs. This configuration may also be used to measure impedance for determining a patient's respiration rate, which may subsequently be used to aid in the regulation and issuance of pacing stimuli to the heart. For instance, a patient whose respiration rate increases due to exercise, for example, may require pacing stimuli to be delivered at a faster rate.

SUMMARY

[0005] In a first general aspect, a method of monitoring pulmonary edema in a human being includes injecting an electrical current between a first electrode located in or around a heart and a housing of a medical device implanted in a chest region. The method also includes measuring a voltage potential between a second electrode in a superior vena cava and a third electrode in the superior vena cava, where the voltage potential is created by the electrical current. The method further includes assessing pulmonary edema based on an impedance value calculated from the electrical current and the voltage potential and a stored edema threshold impedance value.

[0006] Various implementations can include one or more of the following. The injected electrical current may be a cardiac pacing pulse configured to initiate a cardiac cycle, or may be configured such that a cardiac cycle is not initiated in response to injection of the electrical current. The second electrode and the third electrode may positioned on a lead, a distal end of which may be located in a right ventricle. A second voltage potential may be measured between a fourth electrode in the vena cava and either the second electrode or the third electrode, and a second impedance value based on the electrical current and the second voltage potential may be calculated to assess pulmonary edema. Heart enlargement may be assessed based on the calculated impedance values. Relative contributions to impedance changes attributable to pulmonary edema and heart enlargement may be determined by solving a system equations using the calculated impedance values and predetermined coefficients. Two of the second electrode, third electrode and fourth electrode may be positioned on a first lead and the remaining electrode may be positioned on a second lead, or each of the second, third and fourth electrodes may be positioned on a single lead. The current injection, voltage measurement, and impedance value calculation may be repeated on a periodic basis and the assessment of pulmonary edema may include assessing a change in edema based on two or more of the calculated impedance values.

[0007] In a second general aspect, a method of monitoring pulmonary edema in a human being includes injecting an electrical current between a first electrode located in a right ventricle of a heart and a housing of a medical device implanted in a chest region. The method also includes measuring a voltage potential between a second electrode in a superior vena cava and a third electrode in the superior vena cava, where the voltage potential is created by the electrical current. The method further includes assessing pulmonary edema based on an impedance value calculated from the electrical current and the voltage potential and a stored edema threshold impedance value.

[0008] In a third general aspect, a method of monitoring pulmonary edema in a human being includes injecting an electrical current between a first electrode located in a coronary vein of a left ventricle of a heart and a housing of a medical device implanted in a chest region. The method also includes measuring a voltage potential between a second electrode in a superior vena cava and a third electrode in the superior vena cava, where the voltage potential is created by the electrical current. The method further includes assessing pulmonary edema based on an impedance value calculated from the electrical current and the voltage potential and a stored edema threshold impedance value.

[0009] In a fourth general aspect, an implantable medical device includes a housing for the implantable device sized for implantation in a chest region of a patient and comprising a housing electrode. The device also includes a lead port into which a proximal end of a lead is connectable, the lead having first, second, and third conductors that are insulated from one another and that extend from the proximal end of the lead to corresponding first, second, and third electrodes, the third electrode positioned near a distal end of the lead for location in or around a heart, and the first and second electrodes positioned on the lead for location in a superior vena cava. The device also includes an electrical impedance measurement circuit electrically connected to the lead port and the housing electrode. The circuit includes a current generator, a voltage amplifier and a control module, where the current generator is designed to inject an electrical current between the third electrode located in or around the heart and the housing electrode, the voltage amplifier is designed to measure a voltage potential between the first and second electrodes located in the superior vena cava, where the voltage potential is created by the electrical current, and the control module is designed to assess pulmonary edema based on an impedance value calculated from the electrical current and the voltage potential and a stored edema threshold impedance value.

[0010] Various implementations may include one or more of the following. The injected electrical current may be a cardiac pacing pulse configured to initiate a cardiac cycle, or may be configured such that a cardiac cycle is not initiated in response to injection of the electrical current. The current injection, voltage measurement, and impedance value calculation may be repeated on a periodic basis and the assessing pulmonary edema may include assessing a change in edema based on two or more of the calculated impedance values. The control module may be further designed to assess heart enlargement based on the calculated impedance values. Relative contributions to impedance changes attributable to pulmonary edema and heart enlargement may be determined by solving a system equations using the calculated impedance values and predetermined coefficients.

[0011] The details of one or more implementations are set forth in the accompanying drawings and the description below. Other features and advantages will be apparent from the description and drawings, as well as from the claims.

DESCRIPTION OF DRAWINGS

[0012] This document describes these and other aspects in detail with reference to the following drawings.

[0013] FIG. **1** is a perspective diagram of a human heart and lungs.

[0014] FIG. **2** is a diagram of an example implantable device in accordance with an embodiment and the heart and lungs from FIG. **1**.

[0015] FIGS. **3**-**4** are cross-sectional views of a human thorax through the heart and lungs, the cross-sections being indicated in FIG. **1**.

[0016] FIG. **5** is a more detailed view of an embodiment of the device shown in FIG. **2**, showing a block diagram of circuitry within the device and an external device.

[0017] FIGS. **6**A-**6**B are diagrams of an example implantable device.

[0018] FIG. **7** is a more detailed view of an embodiment of the device shown in FIG. **6**, showing a block diagram of circuitry within the device, an external device, and a switch.

[0019] FIGS. **8**A-**8**B are conceptual models of current paths through a human thorax between the electrodes of exemplary implantable devices.

[0020] FIG. **9** is a chart that shows example impedance values at several electrode spacings and lung resistivities.

[0021] FIG. **10** is a flowchart of an example process for measuring biological impedance values for the detection of pulmonary edema.

[0022] Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[0023] Before discussing the medical device used to detect pulmonary edema or thoracic congestion, it will be helpful to discuss first the relative positioning of a human heart and lungs, and the phases of a cardiac cycle. FIG. **1** is an illustrative partial front view of a human heart **12** positioned between a right lung **14***a* and a left lung **14***b*.

[0024] A superior vena cava **24** receives deoxygenated blood from a body's upper extremities and thorax, and empties the blood into a right atrial chamber **16**, referred to as the right atrium. A left atrial chamber (left atrium, not shown in FIG. **1**) conversely receives oxygenated blood from the lungs **14**. The atria (right atrium **16** and left atrium) then contract and force blood into a right ventricular chamber **18** (right ventricle), and left ventricular chamber (left ventricle, covered by the left lung **14***b* in FIG. **1**), respectively. After this atrial contraction, the cardiac cycle reaches the end of diastole, with the ventricles dilated and filled with blood. The right ventricle **18** and left ventricle serve as blood pumps to pump blood away from the heart **12**. The right ventricle **18** pumps deoxygenated blood to the lungs **14** through a pulmonary artery **28**. Within the lungs **14**, the blood becomes reoxygenated and is then moved to the left atrium, as discussed above. The left ventricle, having received oxygenated blood from the lungs **14** through the left atrium, pumps the oxygenated blood to the body through an aorta **26**, a large artery leaving the left ventricle. This second part of the cardiac cycle may be referred to as systole, because the ventricles contract as the blood is pumped therefrom.

[0025] In FIG. **1**, a section of the aorta **26** known as the aortic arch is shown. An inter-ventricular vein **22**, which runs substantially vertically in FIG. **1**, marks a division between the right ventricle **18** and left ventricle. As seen in FIG. **1**, the lungs **14** are close to the heart **12**, the closest portions being the left ventricle and right atrium **16**. The right ventricle **18**, in contrast, is located away from the large volume of lung tissue **14**, approximately between the right lung **14***a* and left lung **14***b* on the anterior side.

[0026] Referring now to FIG. **2**, an illustrative view of the heart and lungs from FIG. **1** and an implantable device **30** is shown. The implantable device **30** includes a housing **32** that houses a lung edema impedance circuit **34**. The lung edema impedance circuit **34** may measure lung impedance and assess pulmonary edema levels. The device **30** includes a right ventricular port **36** for attaching a right ventricular cardiac lead **38**. In FIG. **2**, the lead **38** is attached to the right ventricular (RV) port **36**. The lead **38** may then be introduced into the venous system, down the superior vena cava **24**, into the right atrium **16**, through the tricuspid valve (not shown), and into the right ventricle **18** (visible in FIG. **2** because portions of the lungs **14** have been removed for display purposes).

[0027] In the depicted example, the lead **38** has two electrodes **42***a*, **42***b*, positioned within the superior vena cava, and a tip electrode **205** located in the right ventricle. The electrodes **42***a*, **42***b* are electrically connected to conductors (not shown) that run through the lead **38**. When the lead **38** is attached to the port, the conductors are individually electrically connected to wires or traces within the device **30** that couple the connector port to the lung edema impedance circuit **34**, thereby establishing electrical connections between the circuit **34** and the electrodes. For simplicity, two such wires **44***a*, **44***b* are representatively shown in FIG. **2**, and may be representative of an appropriate number of wires (e.g., three in this example) for separately establishing connections to the electrodes on the lead (electrodes **42***a*, **42***b*, and **205** in this example). For example, the device may include a separate wire that connects the circuit **34** to a connector port for each electrode to be utilized, and this can be extended for implementations having more or fewer electrodes, such as other implementations discussed herein. Electrode **42***a* may be referred to as a proximal electrode, and electrode **42***b* may be referred to as a distal electrode because of their relative positions on the lead **38** with respect to the housing **32**.

[0028] Although electrodes **42***a* and **42***b* are shown as ring electrodes located at particular locations in the superior vena cava, the electrodes **42***a* and **42***b* may be located elsewhere in the vena cava. While the lead **38** is shown in FIG. **2** with three electrodes (**42***a*, **42***b*, **205**), the lead **38** may include additional or fewer electrodes, and may follow a different path through the heart **12** from that shown in FIG. **2**. In some implementations, the electrodes **42***a*, **42***b* can be on the same lead **38** as the current injection electrode (e.g., the tip electrode **205**). In some implementations, any or all of the electrodes can be formed on different leads, as will be discussed in examples described with reference to FIG. **6**.

[0029] A can electrode **46** on an exterior surface of the device housing **32** is electrically connected to the lung edema impedance circuit **34** through a wire **48** to complete a four-electrode configuration. In various embodiments, the implantable device **30** may operate by injecting an electrical current between the tip electrode **205** and the can electrode **46**, for example, and a voltage may be measured between the electrodes **42***a* and **42***b*, which are located in the superior vena cava **24**.

[0030] In some embodiments, the can electrode **46** may be supplemented and/or replaced with a header electrode (not shown). The header electrode may include a conductor located on an exterior surface of a header of the device **30**.

[0031] In operation, the electrodes **42***a*, **42***b* detect a voltage induced by a current injected between the tip electrode **205** located in the right ventricle **18** and the can electrode **46**. The difference between two voltages measured at the electrodes **42***a* and **42***b* may provide information that can be used to assess tissue impedance, for example, in the lungs, heart, and/or muscle tissues. As will be described with reference, for example, to FIG. **8**A, measured voltage in the superior vena cava **24** responsive to a known injected current can be used to measure, assess, and/or estimate impedance of other tissues through which the injected current may flow. In various embodiments, two or more voltage-sensing electrodes may be positioned within the vena cava to measure impedance of one or more tissues based on an injected current, a portion of which passes through those tissues. By way of example, and not limitation, various implementations may advantageously provide improved sensitivity for detecting pulmonary edema and/or ventricular volume change.

[0032] In some embodiments, the implantable device **30** may include additional can, header, or superior vena cava electrodes to facilitate other measurement configurations. Some implantable devices that are configured to perform, for example, tripolar measurements may be changed in structure, operation, and algorithm to include two or more voltage sensing electrodes positioned within the superior vena cava **24**. Examples of apparatuses and methods of using implanted electrodes to perform impedance measurement are described in U.S. Pat. No. 7,313,434, the contents of which are incorporated herein by reference.

[0033] Wires **44***a*, **44***b*, and **48** may be formed, for example, as traces on a printed circuit board, for example. The can electrode **46** may comprise a substantial portion of an external surface of housing **32**, such that the interface impedance of the can electrode **46** is relatively low. The implantable device **30** may be, for example, a pacemaker or defibrillator (or a combination of both), or an infusion pump, and may be sized for implantation in a chest region of a patient. Although the implantable device **30** is shown in FIG. **2** to the left of the heart **12** and lungs **14**, as in a right-sided implant location in a chest region of a patient, the device **30** may alternatively be implanted at a left-sided implant location in a chest region of a patient, such as in a left pectoral region.

[0034] The implementation shown in FIG. **2** may permit current to be injected between an electrode in or around the heart and an electrode on a device implanted in a chest region of a patient. The injected current may induce a voltage potential that can be measured across electrodes positioned in a vena cava of the patient. The injection and measurement can be repeated and measurements can be compared or compared to threshold values to assess physiologic changes in the patient such as lung edema development or heart enlargement, or both. Transfer impedances can be calculated as ratios of the measured voltage potentials divided by the injected currents. Changes in transfer impedances can be monitored. The implementations discussed herein may provide improved sensitivity to these and other physiologic changes, which may permit better and earlier detection of the condition or conditions such that timely interventions may be initiated or modified, if appropriate.

[0035] FIG. **3** shows an anatomical cross-section of FIG. **1** to illustrate a human thorax, including the heart **12** and lungs **14** through a transverse plane that shows the proximity of the left ventricle **20** to the left lung **14***b*. Specifically, FIG. **3** shows coronary veins **54** that can be the location, in some embodiments, for a left ventricular cardiac lead after passing through the coronary sinus **52**. Similarly, the right atrium **16** has a proximal location to the right lung **14***a*, while the right ventricle **18** is not as close to either lung **14***a*, **14***b*. A descending portion **26***a* of the aorta **26** (referred to as the descending aorta), and a sternum **56** are also shown.

[0036] FIG. **4** shows another anatomical cross-section of a human thorax through a superior or higher transverse plane than that shown in FIG. **3**. In FIG. **4**, the superior vena cava **24** is shown entering the right atrium **16**. Similar to the view of FIG. **3**, FIG. **4** shows that the superior portion of right ventricle **18** is not close to the lungs **14**. FIG. **4** shows both the descending aorta **26***a*, and also an ascending portion **26***b* (referred to as the ascending aorta) of the aorta **26**. The left atrium **64** is shown, along with the sternum **56**.

[0037] FIG. **5** shows a block diagram circuit representation of the implantable device **30** from FIG. **2**. Device **30** includes circuits for measuring impedance and making pulmonary edema assessments, and communication circuits for interfacing with external devices. A lung impedance circuit **70** includes a current generator **72**, which may inject an electrical current between two electrodes, such as the tip electrode **205**, which may be positioned within the right ventricle **18** (FIG. **2**) and the can electrode **46** over wire **48** and a conductor through lead **38** (not shown in FIG. **5**). Thus, by virtue of positions of the electrodes, part of the current may flow across the right lung **14***a*. FIG. **5** is a simplified representation of a device, and for simplicity is not intended to show all connections or components that may be included in an actual implanted device of the type discussed herein. For example, the device in FIG. **5** shows only two connections **44***a*, **44***b* to the port **36**, but there may be three, four, five, or more such connections for establishing electrical connections to three, four, five, etc. electrodes on a lead to be attached to the port **36**. For example, the implementation depicted in FIG. **2** may include three wires **44** because the lead **38** includes a tip electrode **205** and two vena cava electrodes **42**. Similarly, the device **30** may include a switch (not shown) that permits any of the electrodes to be configured as a pace or stimulus electrode or a sense electrode with appropriate connection to the sense, pace, current generator, or voltage amplifier block, as desired.

[0038] The injection current may be an alternating current (AC) or a direct current (DC). For example, an AC current may be injected between the current injection electrodes, such as the tip electrode **205** and the can electrode **46**. To avoid undesirable polarization and electrolytic degradation effects at the electrodes and if cardiac stimulation is not desired, the injected current may be of such magnitude, frequency, and duration that it does not cause cardiac stimulation or activation. In one implementation, the AC current may have a frequency of about 50 KHz-100 KHz. Examples of possible current waveforms include sine waves and biphasic pulses (symmetric or otherwise). In some implementations, a cardiac stimulation pacing pulse may be used as the injection current. Alternatively, a DC current can be injected between the current injection electrodes, such as the tip electrode **205** and the can electrode **46**. The current may follow various paths through the chest between the electrodes **205** and **46**. Some of the current passes through the lungs **14***a*, **14***b*. Varying levels of fluid buildup in the lungs **14***a*, **14***b* can cause the lungs **14***a*, **14***b* to present variable impedances to the currents passing through them. Some of the currents also flow through the superior vena cava, and the voltages induced by these currents can be detected by the superior vena cava electrodes **42***a* and **42***b*.

[0039] The injection current between the electrodes **205** and **46** (see FIG. **2**) creates an electric field in the body of a patient. Thus, a voltage potential appears between electrodes **205** and **46**. A voltage amplifier **74** may then measure the voltages sensed between any two electrodes of the system, such as between the electrodes **205** and **46**, or between the electrodes **42***a* and **42***b*. The voltage amplifier may, for example, be a signal-conditioning unit to measure the voltage, and may optionally include a demodulator. In some embodiments, the signal-conditioning may include sampling with analog and/or digital (e.g., IIR, FIR) filtering.

[0040] A control block **76** receives or contains information on the magnitudes of both the injected current and the resulting measured voltage. Analog-to-digital (A/D) converters may be used to translate the information. A processing unit (not shown) such as a microprocessor, microcontroller, or digital signal processor within the control block **76** may then use the current and voltage information to calculate impedance by dividing voltage by current. As body tissue fluid levels increase, the tissue impedance decreases. Thus, the impedance ratio may be used to assess pulmonary edema, and a degree of pulmonary edema may be determined for the patient. An algorithm describing the edema value determination will be discussed later.

[0041] The control block **76**, as is conventional, may additionally include read-only memory (ROM), random-access memory (RAM), flash memory, EEPROM memory, and the like, which may store instructions that may be executed by the processing unit, as well as digital-to analog (D/A) converters, timers, counters, filters, switches, etc. (not shown). Impedance measurements and edema values may also be stored in memory. These control block components may be integrated within a single device, such as an application specific integrated circuit (ASIC), or alternatively may be located in separate devices. Appropriate busses (not shown) allow communication between components within control block **76**.

[0042] Information from a sensor block **78** may be used to adjust the relationship between the measured impedance and the degree of edema. A posture sensor **80** may provide patient orientation information to the control block **76**, allowing posture compensation to be included in the assessment of edema. Because organs and excess fluid in the thorax and lungs **14** tends to shift with posture changes due to gravity, measured impedance may vary as a patient assumes different positions. For example, when some patients lie on a right side, fluid and tissues in the left lung **14***b* may gravitate towards the mediastinum near the superior vena cava electrodes **42**, which may result in lower measured impedance. Thus, based on posture sensor information, the relationship between the impedance measurement and the degree of edema may be adjusted to compensate. Similarly, that relationship may be inversely adjusted for a patient lying on his/her left side. Several types of posture sensors could be used, including mercury switches, DC-accelerometers, or other piezoelectric devices.

[0043] An activity sensor **82**, conventionally used to aid in pacing applications, may also provide information to the control block **76**. By using these compensation schemes, edema interpretation errors caused by postural fluid shifts within a patient may be avoided. Either sensor **80**, **82** may optionally be excluded from the implantable device **30**.

[0044] A telemetry block **84** may communicate wirelessly using radio frequency (RF) transmissions over an antenna **86** with a similarly wirelessly equipped monitoring unit **88**. Monitoring unit **88** may be a computer (custom programmer, desktop, laptop, handheld, etc.), a telemedicine home station, a wearable device such as a wristwatch, or any other appropriate device, and may be used to program the implantable device **30**, or to retrieve information, such as impedance measurements and edema values. A right ventricular sensing/pacing circuit **90** includes a pacing circuit **92** and a sense amplifier **94** and is used to sense and/or stimulate (pace) right ventricular cardiac events. The generic lung edema impedance circuit **34** (FIG. **2**) is not explicitly shown in FIG. **5**, but may include several of the FIG. **5** blocks, or portions thereof. Conventional elements which may further be included in device **30** but are not shown include battery or power supply blocks, defibrillation circuits, and circuits for a left ventricular port.

[0045] FIG. **6**A depicts an exemplary embodiment showing the heart and lungs from FIG. **1** and the implantable device **100**. The implantable device **100** includes a housing **102** that houses a lung edema impedance circuit **104**, and includes a right ventricular port **36** for attaching a right ventricular cardiac lead **38**, and a left ventricular port **106** for attaching a left ventricular cardiac lead **108**. The left ventricular lead **108** may be introduced into the venous system, down the superior vena cava **24**, and on left ventricle **16**, for example by way of the coronary sinus. For example, the left ventricular lead **108** can be located in coronary veins **54** (FIG. **3**) of the left ventricle **16**. In this example, the right ventricular lead **38** has proximal and distal electrodes **42***a*, **42***b* that are electrically connected to conductors (not shown) that run through the right ventricular lead **38**. The conductors connect to conducting wires **44***a*, **44***b*, respectively, within the device **100** when the right ventricular lead **36** is attached to the right ventricular port **36**, establishing electrical connections between the lung edema impedance circuit **104** and the right ventricular electrodes **42***a*, **42***b*. Similar to the right ventricular lead **38**, the left ventricular lead **108** may have additional or fewer electrodes, and/or may alternatively use a tip electrode **305**, for example.

[0046] In the depicted example, the right ventricular lead **38** further includes an electrode **42***c*. The left ventricular lead **108** also includes an electrode **42***d*. In some examples, one or both of the electrodes **42***c*, **42***d* may be positioned at predetermined locations within in the superior vena cava **24**. In some implementations, the electrodes **42***c*, **42***d*, can be used to provide additional spacings for taking impedance measurements between the electrodes **42***c*, **42***d*, and the can electrode **46**, the superior vena cava electrodes **42***a*, **42***b*, and/or the tip electrodes **205**, **305**. By using the electrodes **42***a*-**42***d*, two or more impedance measurements can be made to determine impedance changes caused by, for example, heart enlargement and/or pulmonary edema. The electrodes **42***c* and **42***d* are respectively connected to conductors that run through the respective lead, and to wires (not shown in FIG. **6**A for simplicity) that couple the lung edema impedance circuit **104** to the conductors.

[0047] The arrangement depicted in FIG. **6**A may facilitate lung impedance measurements from the right ventricle **18**, the left ventricle **16**, and the superior vena cava **24**. As such, a more global measurement of lung impedance and hence a more global pulmonary edema assessment may be obtained by using a weighted combination of the multiple impedance measurements. The weighted combination may advantageously retain a high degree of specificity since each lead is anatomically located near the lungs **14**. Furthermore, the combination may allow for a subtraction of common signal contributions from the heart and great vessels thereof, thereby allowing an even more lung-specific measurement.

[0048] In another implementation, FIG. **6**B depicts an exemplary embodiment showing the heart and lungs from FIG. **1** and the implantable device **100**. The right ventricular lead **38** has proximal and distal electrodes **42***a*, **42***b*, **42***c* that are positioned at locations within the superior vena cava **24**. The left ventricular lead **108** includes the electrode **42***d* and further includes an electrode **42***e* positioned within the superior vena cava and distally with respect to the electrode **42***d*.

[0049] In one example implementation configured for left ventricle-only pacing, transfer impedance measurements, such as described herein, may be made via the left ventricular lead **108** and the electrodes **42***d*, **42***e* positioned in the superior vena cava. Accordingly, some embodiments may assess pulmonary edema by making transfer impedance measurements that include electrodes positioned within the superior vena cava to sense voltage without the right ventricular lead **38**, for example.

[0050] FIG. **7** shows a block diagram circuit representation of the example implantable device **100** from FIG. **6**. FIG. **7** is similar to FIG. **5**, with the addition of a left ventricle sensing/pacing circuit **120** for sensing and/or stimulating left ventricle cardiac events, and the addition of the left ventricle port **106**. An implementation may use a single lung impedance circuit **70** and switch connections in succession using switches **122** to obtain the right ventricular and left ventricular impedance measurements. An exploded view of switch **122** is shown in the upper right corner of FIG. **7**. Switches **122** may be controlled by control unit **76** (details not shown in FIG. **7**). As with FIG. **5**, FIG. **7** is a simplified representation not intended to show all connections or components that may be included in an actual implanted device of the type discussed herein. For example, while only two wires are shown connecting to each port for simplicity, an appropriate number of wires may be included so that electrical connections may be established between lead electrodes and device circuits.

[0051] FIGS. **8**A-**8**B are exemplary conceptual models of current paths through a human thorax between the electrodes of the example implantable devices of FIG. **2** and FIG. **6**. The models are simplified circuit representations of current paths through the human thorax. FIG. **8**A shows a conceptual model **800** of an electrical system in one embodiment. The model **800** includes a current source **802** (e.g., the lung edema impedance circuit **34**) that may inject current between the tip electrode **205** and the can electrode **46**. The can electrode **46** has an associated connector interface impedance (Rci1) **804**, and the tip electrode **205** has an associated connector interface impedance (Rci2) **806**. In some implementations, the connector interface impedances **804**, **806** can include impedances associated with tissues that form in response to the implantation of the implantable device **30** and/or the tip electrode **205**.

[0052] The model **800** further includes impedance elements representing impedances in the superior vena cava **24**, the lungs **14***a*, **14***b*, and other tissues that have impedances associated with them. In the depicted example, a current injected by the current source **802** is divided among a superior vena cava impedance (Rsvc) **808**, a lung impedance (Rlungs) **810**, and other tissue impedance (Rother) **812**.

[0053] In some implementations, the superior vena cava impedance (Rsvc) **808** may remain substantially constant, while the lung impedance (Rlungs) **810** may fall substantially as a function of increasing pulmonary edema, for example. Accordingly, voltage measured between electrodes in the superior vena cava may fall in response to injected current shifting away from the Rsvc **808** impedance path as the impedance of the Rlungs **810** path falls in response to increased fluid in the lungs.

[0054] In various embodiments, the location of the voltage sensing electrodes in the superior vena cava may further advantageously reduce the sensitivity of current distribution through Rsvc **808**, Rlungs, **810**, and Rother **812**, and thus the impedance measurement, to changes in heart volume.

[0055] In some implementations, accumulations of fluid in the lungs **14***a*, **14***b* due to pulmonary edema can cause the lung impedance **810** to vary. Two or more electrodes positioned within the superior vena cava **24** can be used to measure an impedance by sensing one or more voltages induced by a current injected via an electrode located in or around the heart. For example, lungs that are substantially free from fluid buildup can have a relatively high value for the lung impedance **810**, whereas lungs with a fluid buildup can have a relatively lower lung impedance **810**. Therefore, in a patient with fluid present in the lungs, the reduced lung impedance **810** may cause the current injected between the tip electrode **205** and the can electrode **46** to proportionally shift away from the superior vena cava **24** (Rsvc) path in favor of a path through the lungs (Rlungs). In some implementations, superior vena cava impedance **808** measurements can vary with the amount of fluid present in the lungs, and these measurements can be used to detect the presence and/or degree of pulmonary edema.

[0056] FIG. **8**B shows a simplified conceptual model **850** of the implantable device **100**. The model **850** also includes a first tissue impedance **860***a* that represents the impedance caused by the tissues that form the current path between the superior vena cava electrodes **42***a*-**42***d* and the first connector interface impedance **804**. A second tissue impedance **860***b* represents the impedance of tissues that contribute to a second current distribution between the superior vena cava electrodes **42***a*-**42***d* and the second connector interface impedance **804**. Examples of tissues that contribute the first tissue impedance **860***a* may include, by way of example and not limitation, the walls of the superior vena cava **24**, the upper portions of the lungs **14***a*, **14***b*, muscles, and/or other tissues that provide an electrical pathway for current. Examples of tissues that can contribute to the tissue impedance measurements may include, by way of example and not limitation, the walls of the superior vena cava **24**, blood, the walls of the heart, lower portions of the lungs **14***a*, **14***b*, muscle tissues, connective tissues (e.g., fascia), fat, and/or other tissues that provide an electrical pathway for current.

[0057] The model **850** includes a first superior vena cava impedance **855***a* and a second superior vena cava impedance **855***b*. The first superior vena cava impedance **855***a* represents the impedance calculated from a first voltage difference **865***a* measured between the superior vena cava electrodes **42***a* and **42***b*. The second superior vena cava impedance **855***b* represents the impedance calculated from a second voltage difference **865***b* measured between the superior vena cava electrodes **42***a* and **42***c*, or between electrodes **42***a* and **42***d*.

[0058] The first voltage difference **865***a* represents the voltage difference associated with the spacing between the superior vena cava electrodes **42***a* and **42***b*, and the second voltage **865***b* represents the voltage difference associated with the spacing between the superior vena cava electrodes **42***a* and **42***c*. In some other examples, two, three, or more voltages can be measured between various other combinations of differently spaced electrodes located in or near the superior vena cava **24** to determine the contributions of impedance changes due to heart enlargement and/or pulmonary edema.

[0059] A number of simulations were conducted using a computer modeling technique. In some examples, simulation results indicate that increased lung impedance measurement sensitivity is possible in various embodiments. A three-dimensional computer model that divides a model of a human thorax into several million small volumes, each corresponding to body tissue, was used to simulate lung impedance under normal and pulmonary edema conditions. Each small tissue volume was assigned an appropriate electrical resistivity (e.g. blood=150 ohms-cm, normal lung=1400 ohms-cm, skeletal muscle=225 ohms-cm, heart muscle=250 ohms-cm, etc.) according to published tables. Electrodes were then placed at various locations in the model, and current may be injected. The simulation program was run on the computer to calculate the resulting voltage potentials at each of the volumes using electric field equations. The results can be used to compute impedance by dividing the measured potentials by the injected current.

[0060] FIG. **9** is a chart **900** that shows example impedance values at several electrode spacings and lung resistivities. In general, simulated tests have shown substantially improved measurement sensitivity for determining a transfer impedance by injecting a current between one pair of implanted electrodes (e.g., the tip electrode **205**, can electrode **46**) and measuring voltage associated with the injected current between another pair of electrodes (e.g., two of the electrodes **42***a*-**42***c*) positioned in the superior vena cava. In various examples, such transfer impedance measurements (using voltage measurements between two sense electrodes that differ from two current injection electrodes used to inject a current that induces the measured voltage, where the transfer impedance is a ratio of such a measured voltage divided by such an injected current) may provide enhanced sensitivity to detect and/or quantify pulmonary edema, and may further advantageously be extended to quantitatively assess how much other tissues (e.g., heart volume) contribute to measured impedance values.

[0061] The chart **900** shows five example curves. The chart **900** includes a tip to can curve **905***a* that represents the percent change in impedance sensed between the tip electrode **205** and the can electrode **46** within a range of lung resistivity values. The chart **900** includes a 7 cm curve **905***b* that represents the percent change in impedance sensed by a pair of superior vena cava electrodes (e.g., a pair of the electrodes **42***a*-**42***d*) spaced 7 cm apart. The chart **900** also includes a 5 cm curve **905***c* that represents the percent change in impedance sensed by a pair of superior vena cava electrodes spaced 5 cm apart, and a 1.5 cm curve **905***d* that represents the percent change in impedance sensed by a pair of superior vena cava electrodes spaced 1.5 cm apart. A SVC to can curve **905***e* represents the percent change in impedance sensed between the can electrode **46** and a single one of the superior vena cava electrodes **42***a*-**42***d*.

[0062] The curves **905***a*-**905***e* represent the results of the previously described simulated tests for measuring the impedances caused by pulmonary edema and heart enlargement. In the simulation, pulmonary edema was simulated by reducing the electrical resistivity of the simulated lung tissue.

[0063] When compared to the tip to can curve **905***a* or the SVC to can curve **905***e*, which involve only a single electrode in the superior vena cava, the curves **905***b*-**905***d* show improved sensitivity by increased percent changes in sensed lung impedance. For example, in a lung with pulmonary edema that exhibits a 1000 Ohm-cm resistivity, the tip to can curve **905***a* and the SVC to can curve **905***e* show an approximately −1% change in sensed impedance, whereas the curves **905***b*-**905***d* show that the 7 cm, 5 cm, and 1.5 cm spaced electrodes exhibit an approximately −7% to −8% change in sensed impedance.

[0064] In lungs that are experiencing pulmonary edema, the buildup of fluid can lower lung resistivity, and the use of spaced electrodes in the superior vena cava **24** can be used to sense the degree of edema with greater sensitivity than can be done by measuring the impedance between the tip **46** and can 205 electrodes alone. For example, in a lung that exhibits a 400 Ohm-cm resistivity, the tip to can curve **905***a* shows an approximately −8% change in sensed impedance and the SVC to can curve **905***e* shows an approximately −10% change, whereas the 7 cm curve **905***b* shows an approximately −28% change. Likewise, the 5 cm curve shows an approximately −30% change, and the 1.5 cm curve shows an approximately −32% change. These simulated results indicate that an approximately 300% improvement in sensitivity to pulmonary edema can be obtained at a lung resistivity of 400 Ohm-cm by using impedance measurements taken from pairs of electrodes spaced in the superior vena cava **24**. Improvements of approximately 600%-800% were determined at a lung resistivity of 1000 Ohm-cm.

[0065] The chart **900** also includes four markers that indicate how much the sensed impedances would change if only the heart enlarged, which is common in heart failure patients. In other words, how measured impedances may be affected by heart enlargement but without pulmonary edema. In the example simulation results, a marker **910***a* represents the impedance change caused by a 30% enlarged heart and sensed between the tip electrode **205** and the can electrode **46**. A marker **910***b* shows the effect of the 30% enlarged heart at superior vena cava electrodes spaced 7 cm apart, a marker **910***c* shows the effect of the 30% enlarged heart at superior vena cava electrodes spaced 5 cm apart, and a marker **910***d* shows the effect of the 30% enlarged heart at superior vena cava electrodes spaced 1.5 cm apart. The marker **910***a* shows that the 30% enlarged heart will cause an approximately −8% change in sensed impedance, whereas the 7 cm curve shows an approximately −17% change. The 5 cm and 1.5 cm curves **905***c*, **905***d*, show that the 30% enlarged heart results in changes of approximately −10% and −5%, respectively. As can be seen in FIG. **9**, the −8% impedance change due to heart enlargement for configuration **905***a* is about the same change as would be seen for a lung resistivity of 400 Ohm-cm for a given severity of pulmonary edema. Similarly, the impedance changes of −17%, −10%, and −5% for configurations **905***b*, **905***c*, and **905***d*, respectively, correspond to impedance changes seen at in edematous patients having lung resistivities of 625 Ohm-cm, 950 Ohm-cm, and 1125 Ohm-cm.

[0066] Implementations discussed herein can be used to inject currents, measure voltages, and calculate impedance values that can be used to solve equations to determine, for example, contributions to impedance changes due to pulmonary edema or heart enlargement.

[0067] FIG. **10** is a flowchart of an example process **1000** for measuring biological impedance values for the detection of pulmonary edema using two or more voltage sensing electrodes positioned in the superior vena cava. The process **1000** begins when a device (e.g., the device **30** of FIG. **2**, or the device **100** of FIG. **6**) is initialized **1005**. In some examples, initialization may include determining coefficients for a system of equations, as discussed elsewhere herein. Various approaches may be used to determine the coefficients (e.g., A, B). For example, a simulation model may be used to separately change the lungs resistivity and heart volume in order to measure the impedance value response(s). This may be particularly effective for a patient who has similar anatomical characteristics to the one used in the model. In some other implementations, initialization may involve measurements associated with body characteristics. For example, predetermined body position changes may be made to manipulate fluid levels and/or distribution. In some examples, a predetermined routine of body positioning may involve a Valsalva Maneuver, which is a respiratory maneuver that can impact heart volume. After initialization **1005**, a number of coefficients are determined **1010**. For example, an impedance measurement (e.g., Z(ab)) can be recorded and stored in a data store for subsequent processing. For example, such subsequent processing may use a formula of the form Z(ab)=A(Z(lung))+B(Z(heart)), where the coefficients A and B can be experimentally determined constants. In some implementations, the coefficients can be determined **1010** from a look-up table or other collection of coefficient values. In some examples, a look-up table may be determined from a model using data for patients of a number of gender, height, and/or weight profiles. In some implementations, the coefficient values can be determined through a self-calibration routine.

[0068] For each electrode spacing measurement that is checked, a corresponding additional equation and an additional unknown may be included in the system of equations to be solved. Each unknown may be defined to correspond to an impedance of an additional tissue. For example, with three electrode spacings for electrodes positioned in the superior vena cava, the measurements may be solved for the relative contributions to impedance and/or impedance values of muscle, lungs, and heart tissues.

[0069] Some further embodiments may include more than two electrodes for injecting current. For example, a system may inject current between an additional electrode positioned in a location adjacent a lung but substantially separate from the can (housing) of the implanted device, thereby providing a substantially altered current distribution for the injected current. Similarly, various combinations of injection electrodes may include one or more injection electrodes positioned in or around the heart, for example. In such embodiments, measurements include potentials sensed at two or more electrodes positioned within the superior vena cava.

[0070] In some implementations, the device can perform an edema check at timed intervals and/or in response to events. For example, the device can be configured to perform an edema check every second, minute, 5 minutes, 15 minutes, hour, day, or other interval. In another example, the device can be configured to perform (or delay performance of) an edema check in response to events sensed by the activity sensor **82** and/or posture sensor **80**, and/or in response to a command received by the telemetry block **84** from the monitoring unit **88**.

[0071] If an edema check is not determined **1015** to be needed, then the process **1000** loops back to continue to await a trigger for an edema check. If an edema check is determined **1015** to be needed, then two electrodes in the superior vena cava are selected **1020**. A current is injected **1025** between the two electrodes, and an impedance is measured **1030** on the selected electrodes. In some implementations, a current is injected between two electrodes different from the SVC electrodes, such as between an electrode in or around the heart and a can electrode on the implantable device, a voltage is measured between the two SVC electrodes, and a transfer impedance is calculated as a ratio of the measured voltage divided by the injected current. The impedance is recorded **1035** in a data store, such as a non-volatile memory of the device.

[0072] If another superior vena cava electrode spacing impedance check is determined **1040** to be needed, then steps **1020-1035** are repeated.

[0073] If another superior vena cava electrode spacing impedance check is not determined **1040** to be needed, then in some implementations, it may be desirable to use multiple impedance checks to measure edema, for example using the same pair of SVC electrodes. For example, bodily motion, aging leads, movement or shifting of the electrodes may briefly interfere with an impedance check, and by using multiple readings any erroneous readings may be detected and ignored.

[0074] If the impedance has not been read successfully **1050** more than once, then another edema check is performed by injecting **1025** current between the electrodes. If the impedance has been read successfully **1050** more than once, then the relative contributions of heart enlargement and pulmonary edema are solved **1055** using the determined coefficients. For example, the formulas Z(ab)=A(Z(lung))+B(Z(heart)) and Z(bc)=C(Z(lung))+D(Z(heart)) can be used. Z(ab) represents the impedance measured between a first and second superior vena cava electrodes, and Z(bc) represents the impedance measured between the second and a third superior vena cava electrodes. By way of example and not limitation, the values A, B, C, and D may be experimentally determined coefficients, or determined from modeling of a particular patient. In some examples, these two equations with two unknowns may be solved for Z(lung)+Z(heart), the contribution of the lungs **14***a*, **14***b* and heart to the impedance change.

[0075] The relative contribution values are stored **1060** in the data store. In some implementations, the values can be later retrieved through the telemetry block **84** by the monitoring unit **88**.

[0076] Although various embodiments have been described with reference to the figures, other examples are possible. For example, the system may capture voltages from each of the two, three, or more superior vena cava electrodes **42***a*-**42***d* at substantially the same time while a current is being injected, and mathematically determine potentials between electrodes of interest.

[0077] In some examples, one or more of the electrode spacings may be referenced to a reference feature or location within the superior vena cava. For example, a reference feature within the superior vena cava **24** may include referring fluoroscopic positioning based upon external reference markers located on the patient's skin, bone structures, or other convenient reference features visible by way of fluoroscopic methods. In some examples, one or more additional leads may provide independent positioning of the superior vena cava electrodes **42***a*-**42***d* relative to one or more predetermined reference features in the superior vena cava **24**. Subsequent monitoring of the position of the superior vena cava electrodes **42***a*-**42***d* relative to a desired position with respect to the reference feature may be used to modify or assess the quantitative measurements of pulmonary edema and/or heart enlargements, for example. As the position of at least one of the superior vena cava electrodes **42***a*-**42***d* deviates from a desired position with respect to the reference feature, confidence in the measured pulmonary edema may decrease, for example.

[0078] Various embodiments may be implemented in systems, apparatus, or methods. In one exemplary aspect, a method for assessing pulmonary edema using an implantable medical device includes a step of injecting an electrical current between a first current electrode and a second current electrode, wherein the first current electrode is located in or around the heart. The method further includes a step of sensing a first voltage induced by the current at a first sense electrode located within the superior vena cava. The method further includes a step of sensing a second voltage induced by the current at a second sense electrode located within the superior vena cava and spaced apart from the first sense electrode. Finally, the method includes a step of determining an impedance value associated with lung tissue based upon the difference between the first and the second sensed voltages.

[0079] In various examples, the exemplary methods may involve assessing pulmonary edema based upon changes in the first impedance. The first current electrode may be positioned within the right ventricle. The second current electrode may be an implanted electrode spaced apart from the first current electrode. The methods may further using a third sense electrode located within the superior vena cava and spaced apart from the first sense electrode and the second sense electrode to sense a third voltage induced by the current. The second voltage difference between the first sense electrode or the second sense electrode and the third sense electrode may be measured to determine a second impedance. The changes in the second impedance may used to assess heart enlargement. The first sense electrode, the second sense electrode, and the first current electrode may commonly reside on a first lead. The first sense electrode, the second sense electrode, the third sense electrode, and the first current electrode may commonly reside on a first lead.

[0080] A number of implementations have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope. For example, advantageous results may be achieved if the steps of the disclosed techniques were performed in a different sequence, if components in the disclosed systems were combined in a different manner, or if the components were replaced or supplemented by other components. The functions and processes (including algorithms) may be performed in hardware, software, or a combination thereof, and some implementations may be performed on modules or hardware not identical to those described. Accordingly, other implementations are contemplated.

1-18. (canceled)

19. A method of monitoring pulmonary edema in a human being, the method comprising:

injecting an electrical current between a first electrode located in or around a heart and a housing of a medical device implanted in a chest region;

measuring a voltage potential between a second electrode and a third electrode, at least one of the second electrode and the third electrode being located in a superior vena cava, the voltage potential created by the electrical current; and

assessing pulmonary edema based on an impedance value calculated from the electrical current and the voltage potential and a stored edema threshold impedance value.

20. The method of claim **19**, wherein the injected electrical current is a cardiac pacing pulse configured to initiate a cardiac cycle.

21. The method of claim **19**, wherein the injected electrical current is configured such that a cardiac cycle is not initiated in response to injection of the electrical current.

22. The method of claim **19**, wherein the second electrode and the third electrode are positioned on a lead, a distal end of which is located in a right ventricle.

23. The method of claim **19**, wherein each of the first, second, and third electrodes is positioned on a single lead.

24. The method of claim **19**, wherein the current injection, voltage measurement, and impedance value calculation is repeated on a periodic basis and the assessing pulmonary edema includes assessing a change in edema based on two or more of the calculated impedance values.

25. The method of claim **19**, wherein the second electrode is in the superior vena cava and the third electrode is in the superior vena cava.

26. The method of claim **19**, wherein the second electrode is in a superior vena cava and the third electrode is not in the superior vena cava, and wherein the third electrode is at the housing of the medical device or at the header of the medical device.

27. The method of claim **19**, wherein each of the second electrode and the third electrode is in a superior vena cava and is located on a first lead, and wherein the first electrode is located on a second lead, different from the first lead.

28. The method of claim **19**, wherein the first electrode is located in a right ventricle of the heart.

29. The method of claim **19**, wherein the first electrode located in a coronary vein of a left ventricle of the heart

30. An implantable medical device, comprising:

a housing for the implantable device sized for implantation in a chest region of a patient and comprising a housing electrode;

a lead port into which a proximal end of a lead is connectable, the lead having first, second, and third conductors that are insulated from one another and that extend from the proximal end of the lead to corresponding first, second, and third electrodes, the third electrode positioned near a distal end of the lead for location in or around a heart;

an electrical impedance measurement circuit electrically connected to the lead port and the housing electrode, the circuit comprising a current generator, a voltage amplifier and a control module, the current generator designed to inject an electrical current between the third electrode located in or around the heart and the housing electrode, the voltage amplifier designed to measure a voltage potential between the first and second electrodes, wherein the voltage potential is created by the electrical current, and the control module designed to assess pulmonary edema based on an impedance value calculated from the electrical current and the voltage potential and a stored edema threshold impedance value.

31. The device of claim **30**, wherein the injected electrical current is a cardiac pacing pulse configured to initiate a cardiac cycle.

32. The device of claim **30**, wherein the injected electrical current is configured such that a cardiac cycle is not initiated in response to injection of the electrical current.

33. The device of claim **30**, wherein the current injection, voltage measurement, and impedance value calculation is repeated on a periodic basis and the assessing pulmonary edema includes assessing a change in edema based on two or more of the calculated impedance values.

34. The device of claim **30**, wherein the control module is further designed to assess heart enlargement based on the calculated impedance values.

35. The device of claim **24**, wherein relative contributions to impedance changes attributable to pulmonary edema and heart enlargement are determined by solving a system equations using the calculated impedance values and predetermined coefficients.

36. The device of claim **30**, wherein the first electrode is positioned on the lead for location in a superior vena cava.

37. The device of claim **30**, wherein the second electrode is positioned on the lead for location in a superior vena cava.

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专利名称(译)	使用bioimpedance监测心力衰竭		
公开(公告)号	US20140303512A1	公开(公告)日	2014-10-09
申请号	US14/251948	申请日	2014-04-14
[标]申请(专利权)人(译)	明尼苏达大学		
申请(专利权)人(译)	明尼苏达大学校董会		
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IPC分类号	A61B5/00 A61B5/053		
CPC分类号	A61B5/053 A61B5/4878 A61B5/0535 A61N1/36521		
优先权	PCT/US2009/060223 2009-10-09 WO 61/104631 2008-10-10 US		
外部链接	Espacenet USPTO		

摘要(译)

在监测人体肺水肿的方法中，在位于心脏内或心脏周围的第一电极与植入胸部区域的医疗装置的壳体之间注入电流。在上腔静脉中的第二电极和上腔静脉中的第三电极之间测量电压电势，其中电压电势由电流产生。基于根据电流和电压电势计算的阻抗值和存储的水肿阈值阻抗值来评估肺水肿。