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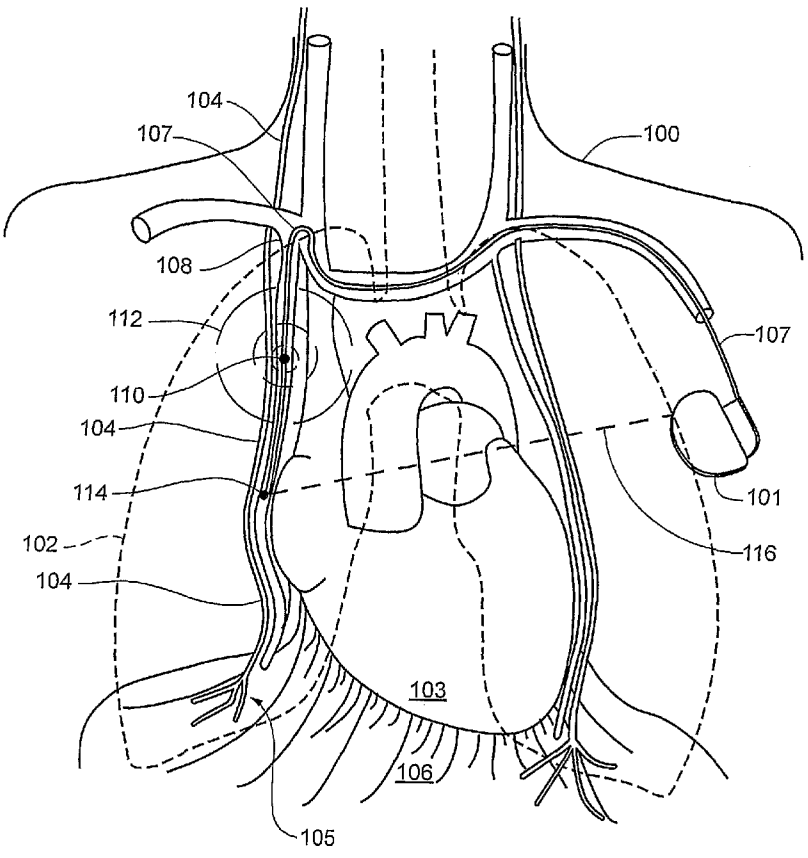
(54) Title: SYSTEM AND METHOD TO MODULATE PHRENIC NERVE TO PREVENT SLEEP APNEA



(57) Abstract: An implantable medical device for treating breathing disorders such as central sleep apnea wherein stimulation is provided to the phrenic never through a transvenous lead system with the stimulation beginning after inspiration to extend the duration of a breath and to hold the diaphragm in a contracted condition.

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SYSTEM AND METHOD TO MODULATE PHRENIC NERVE TO PREVENT SLEEP APNEA

CROSS-REFERNCE TO RELATED CASES

This case claims priority from and the benefit thereof and incorporates entirely: U.S. Provisional Application 60/737,808, filed 11/18/2005, and entitled "System and Method to Modulate Phrenic Nerve to Prevent Sleep Apnea;" U.S. Provisional Application 60/743,062, filed 12/21/2005, and entitled "System and Method to Modulate Phrenic Nerve to Prevent Sleep Apnea;" and U.S. Provisional Application 60/743,326, filed 2/21/2006, and entitled "System and Method to Modulate Phrenic Nerve to Prevent Sleep Apnea."

FIELD OF THE INVENTION

The present invention relates generally to implantable medical devices and more particularly to a device and method for controlling breathing and for treating Central Sleep Apnea.

BACKGROUND OF THE INVENTION

History

Sleep Disordered Breathing (SDB) and particularly Central Sleep Apnea (CSA) is a breathing disorder closely associated with Congestive Heart Failure (CHF). The heart function of patients with heart failure may be treated with various drugs, or implanted cardiac pacemaker devices. The breathing function of patients with heart failure may be treated with Continuous Positive Air Pressure (CPAP) devices or Nocturnal Nasal Oxygen. These respiratory therapies are especially useful during periods of rest or sleep. Recently, implanted devices to directly address respiration disturbances have been proposed. Some proposed therapeutic devices combine cardiac pacing therapies with phrenic nerve stimulation to control breathing.

Phrenic nerve pacing as a separate and stand alone therapy has been explored for paralyzed patients where it is an alternative to forced mechanical ventilation, and for patients with the most severe cases of central sleep apnea. For example, Ondine's Curse has been treated with phrenic nerve pacemakers since at least the 1970's. In either instance, typically, such phrenic nerve pacemakers place an electrode in contact with the phrenic nerve and they pace the patient's phrenic nerve at a constant rate. Such therapy does not permit natural breathing and it occurs without regard to neural respiratory drive.

Motivation for Therapy

SDB exists in two primary forms. The first is central sleep apnea (CSA) and the second is obstructive sleep apnea (OSA). In OSA the patient's neural breathing drive remains intact, but the pulmonary airways collapse during inspiration, which prevents air flow causing a form of apnea. Typically, such patients awake or are aroused as a result of the apnea event. The forced airflow of CPAP helps keep the airways open providing a useful therapy to the OSA patient.

CSA patients also exhibit apnea but from a different cause. These CSA patients have episodes of reduced neural breathing drive for several seconds before breathing drive returns. The loss of respiratory drive and apnea is due to a dysfunction in the patient's central respiratory control located in the brain. This dysfunction causes the patient's breathing pattern to oscillate between too rapid breathing called hyperventilation and periods of apnea (not breathing). Repeated bouts of rapid breathing followed by apnea are seen clinically and this form of disordered breathing is called Cheyne-Stokes breathing or CSR. Other patterns have been seen clinically as well including bouts of hyperventilation followed by hypopneas only.

In patients with CHF, prognosis is significantly worse when sleep apnea is present. A high apnea-hypopnea index (a measure of the number of breathing disturbances per hour) has been found to correlate to a poor prognosis for the patient. The swings between

hyperventilation and apnea characterized by central sleep apnea have three main adverse consequences, namely: large swings in arterial blood gases (oxygen and carbon dioxide); arousals and shifts to light sleep; and large negative swings in intrathoracic pressure during hyperventilation. The large swings in blood gases lead to decreased oxygen flow to the heart, activation of the sympathetic nervous system, endothelial cell dysfunction, and pulmonary arteriolar vasoconstriction. Arousals contribute to increased sympathetic nervous activity, which has been shown to predict poor survival of patients with heart failure. Negative intrathoracic pressure, which occurs during the hyperventilation phase of central apnea, increases the after load and oxygen consumption of the left ventricle of the heart. It also causes more fluid to be retained in the patient's lungs. As a result of these effects the patient's condition deteriorates.

In spite of advances in care and in knowledge there is a large unmet clinical need for patients with sleep disordered breathing especially those exhibiting central sleep apnea and congestive heart failure.

SUMMARY OF THE INVENTION

The device of the present invention can sense the patients breathing and it can distinguish inhalation or inspiration from exhalation or expiration.

The device can periodically stimulate the phrenic nerve as required. In some embodiments the stimulation may be invoked automatically in response to sensed physiologic conditions. In some embodiments the device can stop the delivery of therapy in response to sensed conditions. In some embodiments the device can be prescribed and dispensed and the therapy delivered without regard to the sensed conditions. As a result, the device may be used to detect and intervene in order to correct episodes of sleep disordered breathing or the device may intervene to prevent episodes of sleep disordered breathing from

occurring. The methods that are taught here may be used alone to treat a patient or they may be incorporated into a cardiac stimulating device where the respiration therapy is merged with a cardiac therapy. The therapy and its integration with cardiac stimulation therapy and the architecture for carrying out the therapy are quite flexible and may be implemented in any of several forms.

Hardware implementation and partitioning for carrying out the methods of the invention are also flexible. For example the phrenic nerve stimulation may be carried out with a transvenous lead system lodged in one of the cardiophrenic vein a short distance from the heart. One or both phrenic nerves may be accessed with leads. Either one side or both (right and left) phrenic nerves may be stimulated. Alternatively the phrenic nerve may be accessed through a large vein such as the jugular or the superior vena cava. As an alternative a stimulation electrode may be place in the pericardial space on the heart, near the phrenic nerve but electrically isolated from the heart. Implementation of respiration detection may also take any of several forms. Transthoracic impedance measurement may be taken from electrodes implanted at locations in the body to measure or sense the change in lung volume associated with breathing. Alternatively one or more implanted pressure transducers in or near the pleural cavity may be used to track pressure changes associated with breathing. Knowledge of breathing rates and patterns are useful in carrying out the invention but distinguishing reliably the inspiration phase from expiration phase is a breath is particularly important for timing the delivery of the stimulation.

We consider that breathing has an inspiration phase followed by an expiration phase. Each breath is followed by a pause when the lungs are "still" before the next breath's inspiration. The device delivers phrenic nerve stimulation after the start of inspiration preferably toward the start of exhalation. The duration and magnitude of the stimulation is selected to "extend" the expiration phase or the respiratory pause of a naturally initiated breath. We note relatively little

change in lung volume and little air exchange during the stimulation phase of the therapy. We have observed that prolongation of a natural breath, while keeping some air trapped in the lungs, delays the inspiration phase of next natural breath until the air trapped in the lungs is exhaled. For this reason our therapy has a tendency to lower the observed breathing rate. Typically the stimulation maintains activation of the diaphragm long enough to mimic a patient holding their breath by not letting the diaphragm relax. This mechanism of action controls the rate of breathing by increasing the effective duration of each breath.

Our experimental animal work has demonstrated the ability of the stimulation regime to down-regulate breathing rate (and minute ventilation) to a desired (preset) value while maintaining natural inspiration (i.e. by prolonging exhalation and extending the respiratory pause phases of the breath) without blocking the phrenic nerve. We believe that maintenance of natural inspiration is important since it allows prevention of airway collapse and retains certain capacity of the body to auto regulate rate of inspiration and depth of breathing. We also demonstrated that unilateral and transvenous stimulation is sufficient to carry out the invention and insures adequate levels of patient safety. In the process of prolonging the respiratory pause we "stilled" the lungs (no air movement occurred) while keeping one lung inflated. We believe that the mechanism of action for this observed effect is a physiologic feedback that prevents the respiration control center of the central nervous system from initiating the following breath. In other words we have invented a novel and practical therapy by substantially immobilizing at least one lung of the patient by maintaining the diaphragm in the contracted state by transvenous electrical stimulation of a phrenic nerve for the duration sufficient to substantially reduce breathing rate and alter the blood gas composition of the patient.

BRIEF DESCRIPTION OF THE DRAWINGS

A preferred embodiment and best mode of the invention is illustrated in the attached drawings where identical reference numerals indicate identical structure throughout the figures and where multiple instances of a reference numeral in a figure show the identical structure at another location to improve the clarity of the figures, and where:

Figure 1 is a schematic diagram;

Figure 2 is a schematic diagram;

Figure 3 is a schematic diagram;

Figure 4 is a schematic diagram;

Figure 5 is diagram showing experimentally derived physiologic data displayed in two panels A and B;

Figure 6 is a schematic diagram showing physiologic data known in the prior art; and

Figure 7 is a schematic diagram showing physiologic data and device timing information.

DETAILED DESCRIPTION OF THE INVENTION

Figure 1 is schematic diagram showing an implanted medical device (IMD) 101 implanted in a patient's chest for carrying out a therapeutic stimulation of respiration. The patient has lungs shown in bold outline and indicated at 102 overlying the heart 103. The right phrenic nerve 104 passes from the head alongside the heart to innervate the diaphragm 106 at location 105.

In this embodiment a transvenous lead 107 passes from the IMD 101 and passes through venous vasculature to enter the cardiophrenic vein 108 on the right side of the patient. The cardiophrenic vein 108 lies next to the phrenic nerve 104 along the heart. Electrical stimulation pulses supplied to the stimulation electrode 110 on lead 107 interact with the phrenic nerve to stimulate it and thus activate the diaphragm 106. In the figure a series of concentric circles 112 indicate electrical

stimulation of the phrenic nerve. In this embodiment the stimulation electrode 110 lies far enough away from the heart 103 to avoid stimulating the heart 103. In this embodiment only one branch of the phrenic nerve 104 is stimulated and the other side of nerve is under normal physiologic control.

A respiration electrode 114 on lead 107 cooperates with an indifferent electrode on the can of the IMD 101 to source and sink low amplitude electrical pulses that are used to track changes in lung volume over time. This well known impedance plethysmography technique is used to derive the inspiration and expiration events of an individual breath and may be used to track breathing rate. This impedance measurement process is indicated in the diagram by the dotted line 116 radiating from the electrode site of respiration electrode 114 to the IMD 101. Transvenous stimulation of the phrenic nerve from a single lead carrying an impedance measuring respiration electrode is a useful system since it permits minimally invasive implantation of the system. However other architectures are permissible and desirable in some instances.

Figure 2 is a schematic diagram showing alternative electrode and lead placements for use in carrying out the stimulation regime of the invention. In some patients it may be easier or more suitable to access the phrenic nerve in the neck in the jugular vein at electrode location 200. In some instances it may be preferable to place electrodes in veins both near the right phrenic nerve as indicated by the deep location of a stimulation electrode 110 and in the left phrenic nerve at electrode location 202. Other potential locations for the stimulation electrodes are the large vessel (SVC) above the heart indicated by electrode 203. Unilateral stimulation is preferred but having multiple sites available may be used to reduce nerve fatigue. Non-venous placement is possible as well. For example, placement of a patch electrode in the pericardial space between the heart and within the pericardial sac is suitable as well, as indicated by electrode location 205. In this embodiment the insulating patch 206 isolates spaced electrodes

207 and electrode 208 from the heart. The lead 204 connects this bipolar pair of electrodes to the IMD 101.

Also seen in this figure is a pressure transducer 209 located in the pleural cavity and connected to the IMD 101 via a lead. The pressure transducer 209 tracks pressure changes associated with breathing and provides this data to the implanted device 101. The pressure transducer is an alternative to the impedance measurement system for detecting respiration. Such intraplueral pressure signal transducers are known in the respiration monitoring field.

Figure 3 shows a schematic diagram of a system for carrying out the invention. The system has an implanted portion 300 and an external programmer portion 301.

The IMD 101 can provide stimulation pulses to the stimulation electrode 110. A companion indifferent electrode 306 may be used to sink or source the stimulation current generated in analog circuits 303. A portion of the exterior surface 302 of the IMD 101 may be used with respiration electrode 114 to form an impedance plethysmograph. In operation, logic 305 will command the issuance of a train of pulses to the respiration electrode 114 and measure the amplitude of the signal as a function of time in circuits 304. This well known process can measure the respiration of the patient and find the inspiration phase and the expiration phase of a breath. Respiration data collected over minutes and hours can be logged, transmitted, and/or used to direct the therapy.

When the therapy is invoked by being turned on by the programmer 301 or in response to high rate breathing above an intervention set point, the logic 305 commands the stimulation the phrenic nerve via the stimulation electrode 110 at a time after the beginning of the inspiration phase. Preferable the stimulation begins after the onset of exhalation. There is some flexibility in onset of stimulation. The shape of the stimulation pulses is under study and it may be beneficial to have the logic 305 command stimulation at higher amplitudes of energy levels as the stimulation progresses. It may also

be desirable to have stimulation ramp up and ramp down during the therapy. It may prove desirable to stimulate episodically. The therapy may be best administered to every other breath or in a random pattern. The programmer may permit the patient to regulate the therapy as well. However in each case the stimulation of the diaphragm "stills" the diaphragm resulting in an amount of air trapped in at least one lung and extends the breath duration.

The duration of the stimulation is under the control of logic 305. It is expected that the therapy will be dispensed with a fixed duration of pulses corresponding to breathing rate. It should be clear that other strategies for setting the duration of stimulation are within the scope of the invention. For example the breathing rate data can be used to set the stimulation duration to reduce breathing rate to a fraction of the observed rate. The therapy may also be invoked in response to detected high rate breathing or turned on at a fixed time of day. In a device where activity sensors are available the device may deliver therapy at times of relative inactivity (resting or sleeping).

Figure 4 shows a schematic diagram of an alternate partitioning of the system. In this implementation, the respiration sensing is carried out outside the patient with sensor 404, while the implanted portion 400 communicates in real time with an external controller 401 via coils 403 and 402. This respiration sensor 404 may be a conventional respiration belt or thermistor based system. Real time breathing data is parsed in the controller 401 and control signal sent to the IPG 101 to drive stimulation of the phrenic nerve via lead 107. This implementation simplifies IMD 101 portion for the system and may be useful for delivery of therapy to a resting or sleeping patient.

Figure 5 is set forth as two panels. The data collected from an experimental animal (pig) is presented in the two panels and should be considered together. Panel 5B plots airflow into and out of the animal against time, while panel 5A plots volume against time. In the experiment the volume data was computed (integrated) from the airflow measurement. The two panels are two ways of looking at the

same data collected at the same time. In each panel the dotted tracing 500 in 5B and 502 in panel 5A represent the normal or natural or not-stimulated and therefore underlying breathing pattern of the animal. In panel 5A the inspiration phase of tracing 502 is seen as segment 514. After tracing 502 peaks, the expiration phase begins as indicated by segment 516. The figure shows that along trace 502, the air that is inhaled is exhaled before 2 seconds has elapsed, as indicated by the dotted trace 502 returning to the zero volume level.

Trace 504 is associated with the unilateral delivery of stimulation 508 to a phrenic nerve. In the tracing the start of stimulation at time 518 is well after the start of inspiration and corresponds approximately to the reversal of airflow from inspiration to expiration as seen at time 518. Very shortly after the stimulation begins the animal inhales more air seen by the "bump" 520 in the tracing 504 in panel 5B. A small increment in the total volume corresponding to this bump is seen at the same time in panel 5A. Of particular interest is the relatively flat tracing 522 corresponding to no significant change in lung volume during stimulation. Once stimulation terminates the lungs expel air as seen at volume change 524 in panel 5A corresponding to outflow labeled 512 in panel 5B. Only after the exhalation outflow 512 was complete did the sedated experimental animal initiate the next breath (not shown). Thus duration of breath was extended in this case from approximately 2 seconds to approximately 6 seconds resulting in the breathing rate reduction from 30 to 10 breaths per minute. The data support the assertion that adequate phrenic stimulation initiated after inspiration and during expiration can "prolong" or "hold" the breath and thus regulate or regularize breathing which it the value of the invention.

Figure 6 shows a bout 601 of rapid breathing 603 followed by or preceded by apnea 602 events. This waveform is a presentation of Cheyne-Stokes respiration (CSR) well known in the prior art. The corresponding tracing of blood gas 607 indicates that the rapid breathing drives off blood carbon dioxide (CO2) as indicated the slope of line 606. CSR begins with the rise of CO2 as indicated by ramp line

605 which triggers the rapid breathing. The ventilation drives the CO2 too low resulting in a loss of respiratory drive and an apnea event 602. During the apnea the level of CO2 rises as indicated by the slope of line 604. Once a threshold is reached the cycle repeats.

Figure 7 shows a schematic diagram showing the delivery of the inventive therapy in the context of a patient experiencing CSR respiration. The patient experiences several quick breaths 701 and then the device is turned on as indicated by the stimulation pulses 709. The device looks for a natural inspiration and waits until about the turn from inspiration to expiration, then the burst 709 of stimulation is delivered to a phrenic nerve. As explained in connection with figure 5 the stimulation delays breath 706. This next breath is also a candidate for the therapy and stimulation burst 710 is delivered to the phrenic nerve delaying breath 707. In a similar fashion the device intervenes in breaths 707 and 708. It is expected that the lower rate breathing resulting from repeated application of the therapy will keep the CO2 level in a "normal" range 715 and prevent CSR. The therapy could also be invoked in response to a detected bout of CSR but this is not necessary and it is believed that keeping a patient out of CSR is the better therapy.

It may be noted that the stimulation waveforms vary in Figure 7 with stimulation 710 rising in amplitude while stimulation 711 decreases in amplitude. Note as well that stimulation 712 ramps up and then down during the therapy. It is expected that the best waveform may vary from patient to patient or may vary over time. Also seen in the figure is a refractory period typified by period 730 that may be implemented in the logic 302 to prevent the device from issuing the therapy too close in time to the last intervention. In general the refractory period effectively disables the deliver of therapy until the refractory period expires. This places an effective low rate on stimulated rate of breathing. The refractory may be fixed, programmable or adjusted based on sensed breathing rate.

WHAT IS CLAIMED IS:

1. A method of treating a breathing disorder in a patient having a lung, a diaphragm innervated by a phrenic nerve and a vein near the phrenic nerve, the method comprising:

implanting a stimulation electrode in a vein of the patient proximate the phrenic nerve;

measuring the respiration of the patient, to find the inspiration phase of a breath;

stimulating the phrenic nerve via the stimulation electrode at a time beginning after the beginning of the inspiration phase;

whereby said stimulation of the diaphragm stills the diaphragm resulting in substantial amount of air trapped in at least one lung.

2. The method of claim 1 wherein:

said stimulation step begins at a time beginning after the start of the inspiration phase and extends past said normal observable expiration phase;

whereby the observed breathing rate of the patient decreases.

3. The method of claim 1 wherein:

said stimulation step begins at a time beginning after the start of the inspiration phase and extends past said normal observable expiration phase;

whereby the next breath is delayed with reference to a normal breathing rate.

4. The method of claim 1 wherein:

said stimulation step begins at a time beginning after the start of the inspiration phase and extends past said normal observable expiration phase;

whereby the next start of inspiration is delayed with reference to a normal breathing rate.

5. A method of treating a patient comprising:

implanting a stimulation electrode of the patient proximate the phrenic nerve;

detecting the start of a natural breath;

stimulating the phrenic nerve with the stimulation electrode after the beginning of the breath while the airway is open and stimulating for an extended time sufficient to lower the observed breathing rate of said patient by delaying the start of the next natural breath of said patient;

thereby raising the CO2 level of the patient sufficient to prevent the onset of hyperapnea.

6. The method of claim 5 wherein:

said stimulation electrode is placed in a vein.

7. The method of claim 5 wherein:

said stimulation electrode is placed in the pericardial space.

8. The method of claim 5 wherein:

said stimulation electrode is placed in a cardiophrenic vein.

9. The method of claim 5 wherein:

said stimulation electrode is placed in a jugular vein.

10. A implantable device for treating a breathing disorder in a patient having a lung, a diaphragm innervated by a phrenic nerve and a vein near the phrenic nerve, the method comprising:

a lead having a stimulation electrode adapted for implantation in a vein of the patient proximate the phrenic nerve;

a respiration measuring device for monitoring the respiration of the patient, to find the inspiration phase of a breath;

a stimulator for stimulating the phrenic nerve with the stimulation electrode at a time beginning after the beginning of the inspiration phase, and the duration and magnitude of the stimuli sufficient to still the diaphragm of the patient resulting in substantial amount of air trapped in at least one lung, for a long enough time to inhibit the beginning of the next breath, thereby reducing the breathing rate of the patient.

Fig. 1

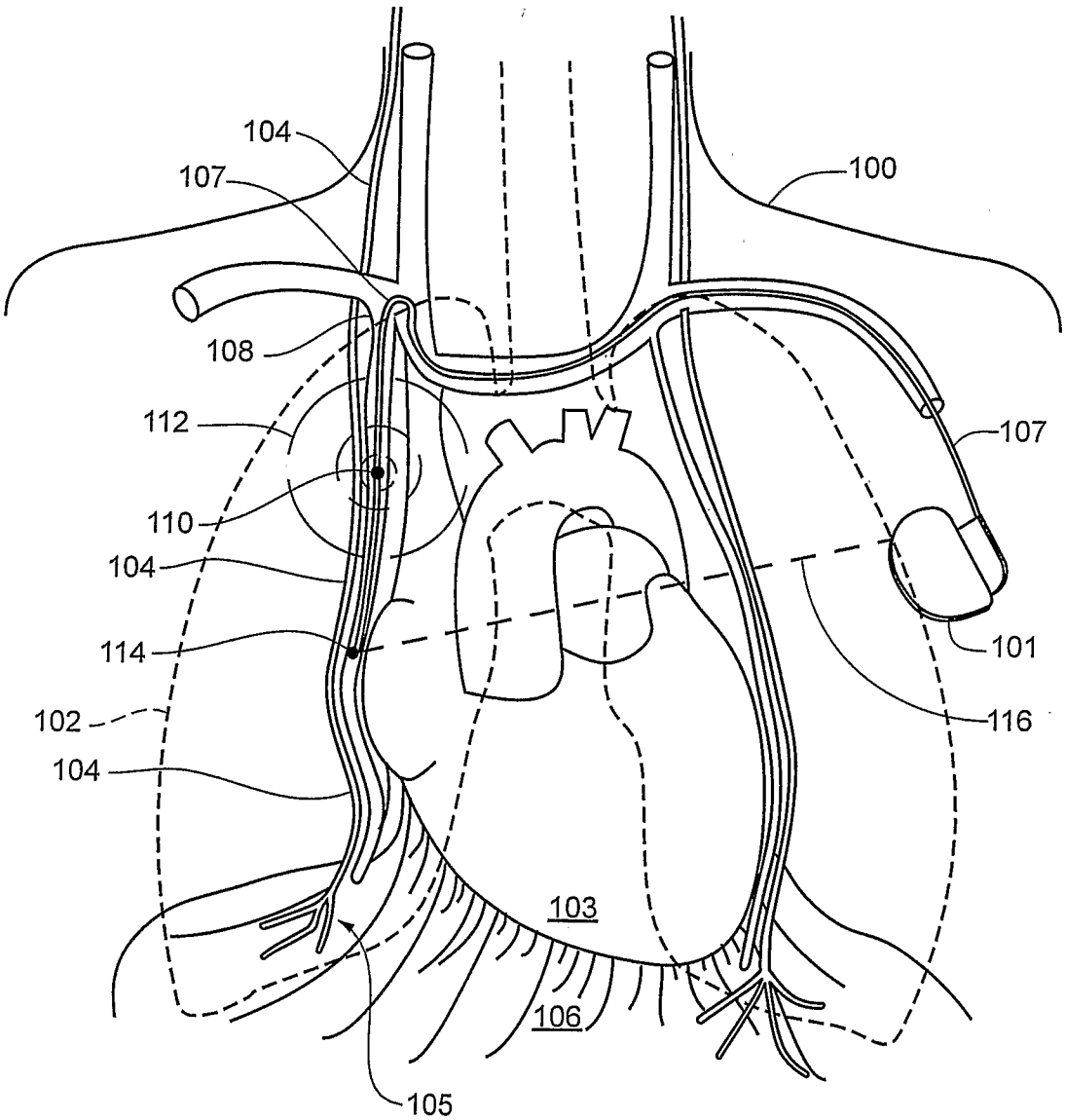


Fig. 2

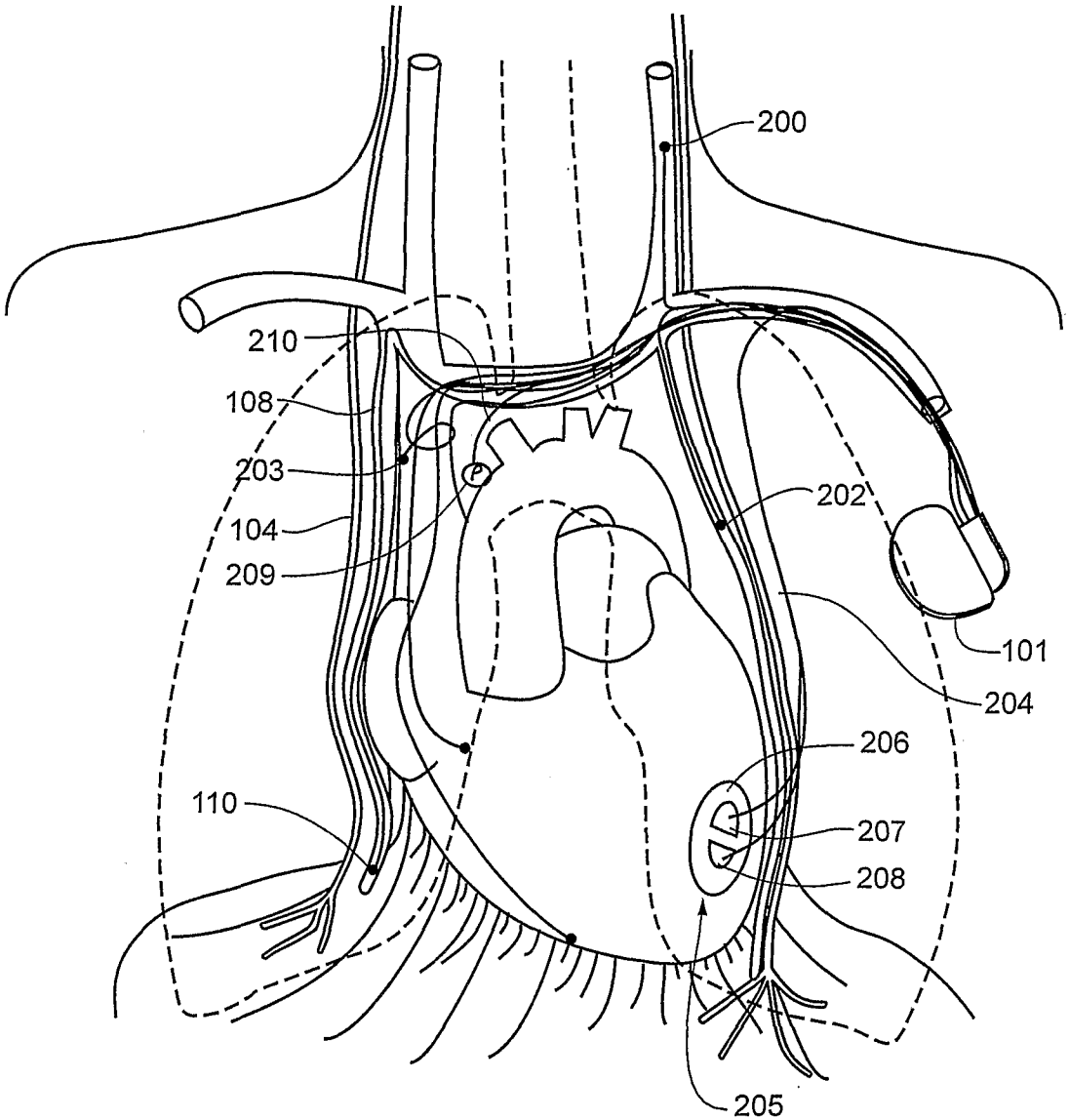
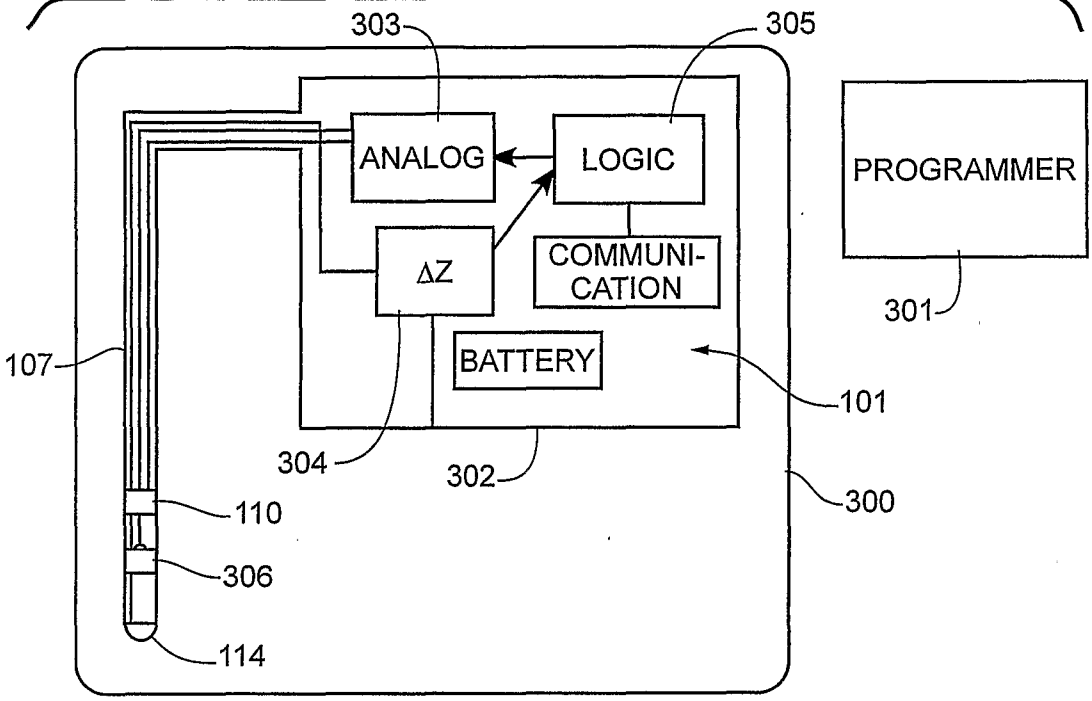


Fig. 3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305
ANALOG
LOGIC
PROGRAMMER
ΔZ
COMMUNI-
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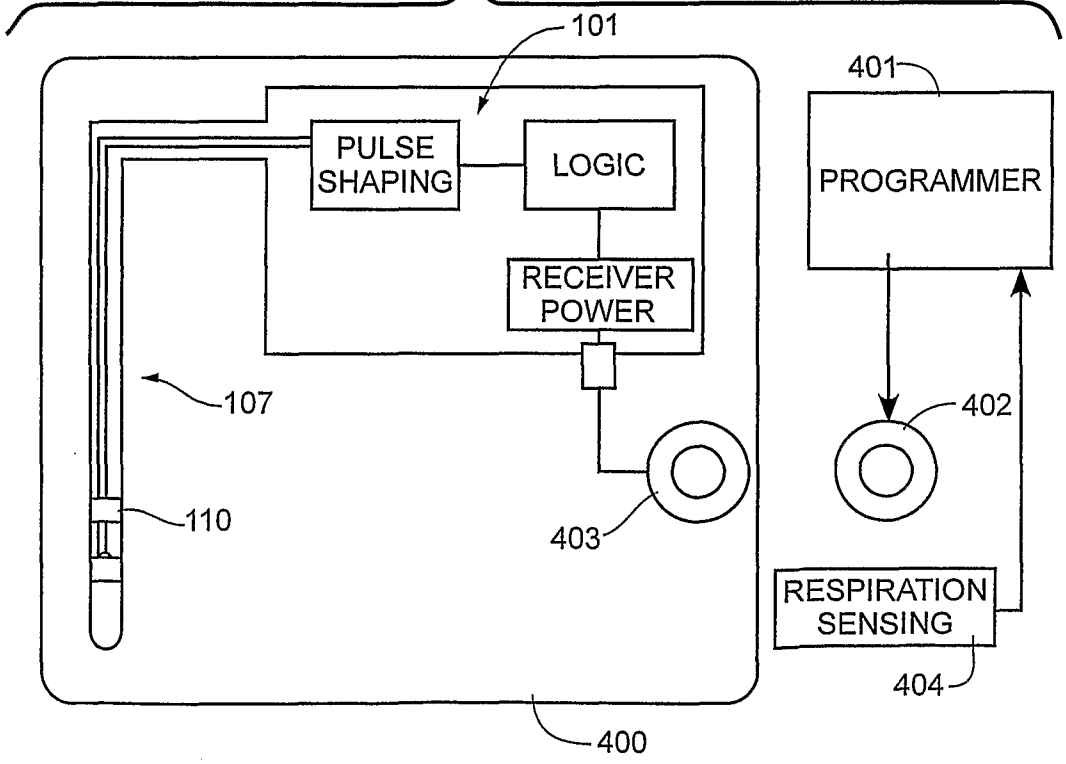
BATTERY
101
304
302
300
110
306
114

Fig. 4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RESPIRATION
SENSING
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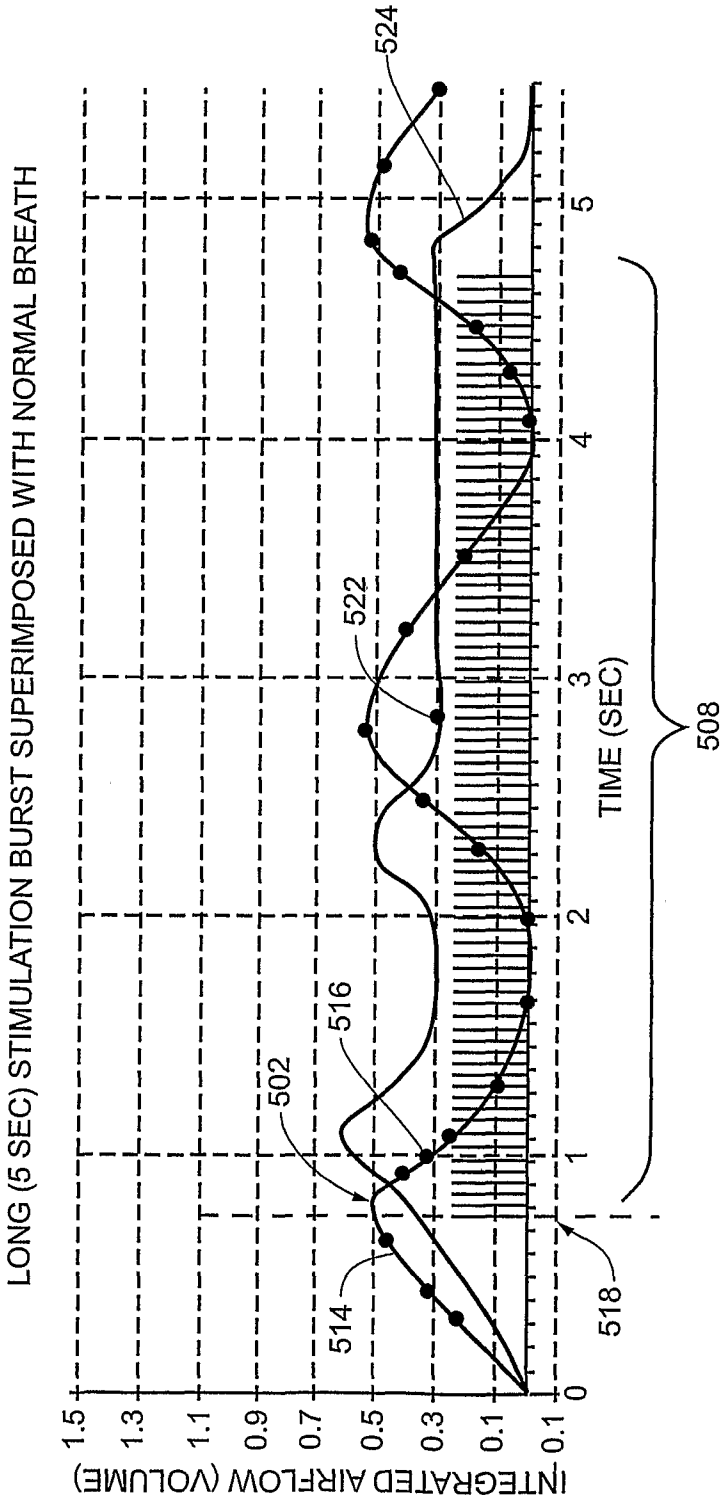
400

Fig. 5A


LONG (5 SEC) STIMULATION BURST SUPERIMPOSED WITH NORMAL BREATH
INTEGRATED AIRFLOW (VOLUME)
1.5
1.3
1.1
0.9
0.7
0.5
0.3
0.1
0.1
0
1
2
3
4
5
TIME (SEC)
502
514
516
518
522
524
508

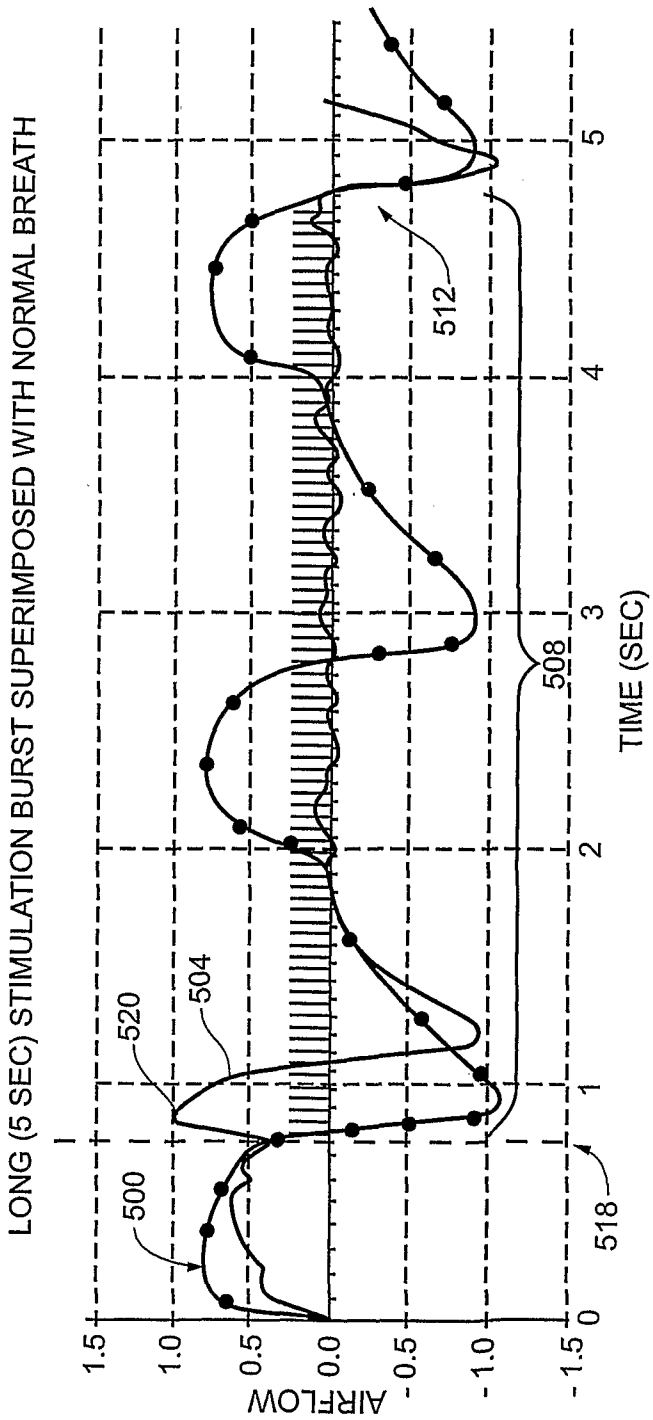

LONG (5 SEC) STIMULATION BURST SUPERIMPOSED WITH NORMAL BREATH
AIRFLOW
TIME (SEC)
1.5
1.0
0.5
0.0
- 0.5
- 1.0
- 1.5
0
1
2
3
4
5
500
504
508
512
518
520

Fig. 5B

Fig. 6
PRIOR ART

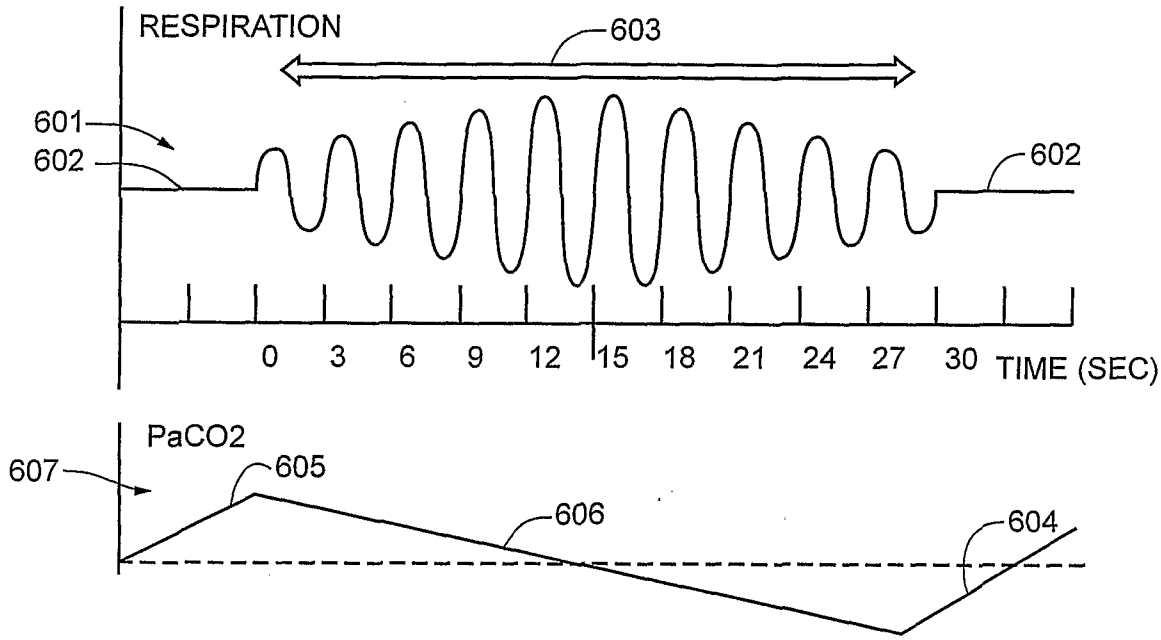


Fig. 7