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(54) **DETECTING AND TREATING DISORDERED BREATHING**

(71) Applicant: **Respicardia, Inc.**, Minnetonka, MN (US)

(72) Inventors: **Mark Gelfand**, New York, NY (US); **Howard Levin**, Teaneck, NJ (US); **Andrew Halpert**, Coral Springs, FL (US); **Antonis Panteleon**, Edina, MN (US)

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(57) **ABSTRACT**

Detection and treatment of disordered breathing is disclosed, with treatment being primarily delivered using electrical stimulation of the diaphragm, either directly or by stimulating appropriate nerves.

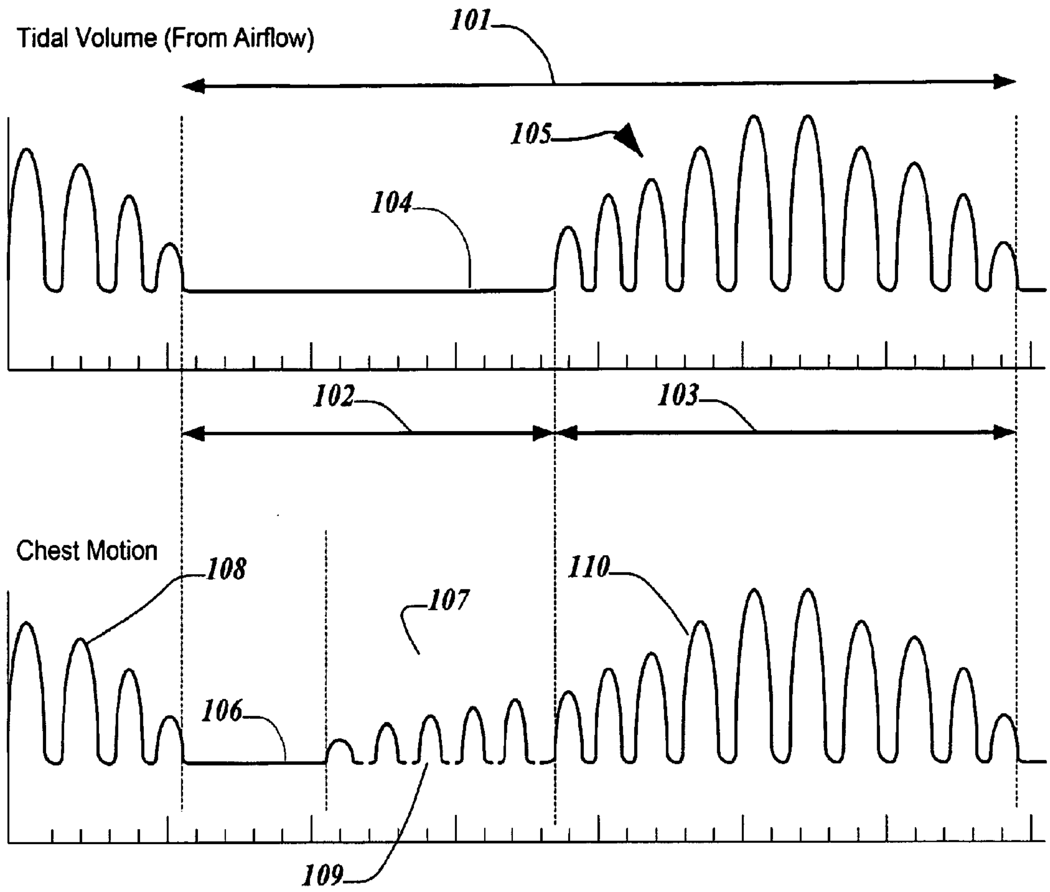


Figure 1

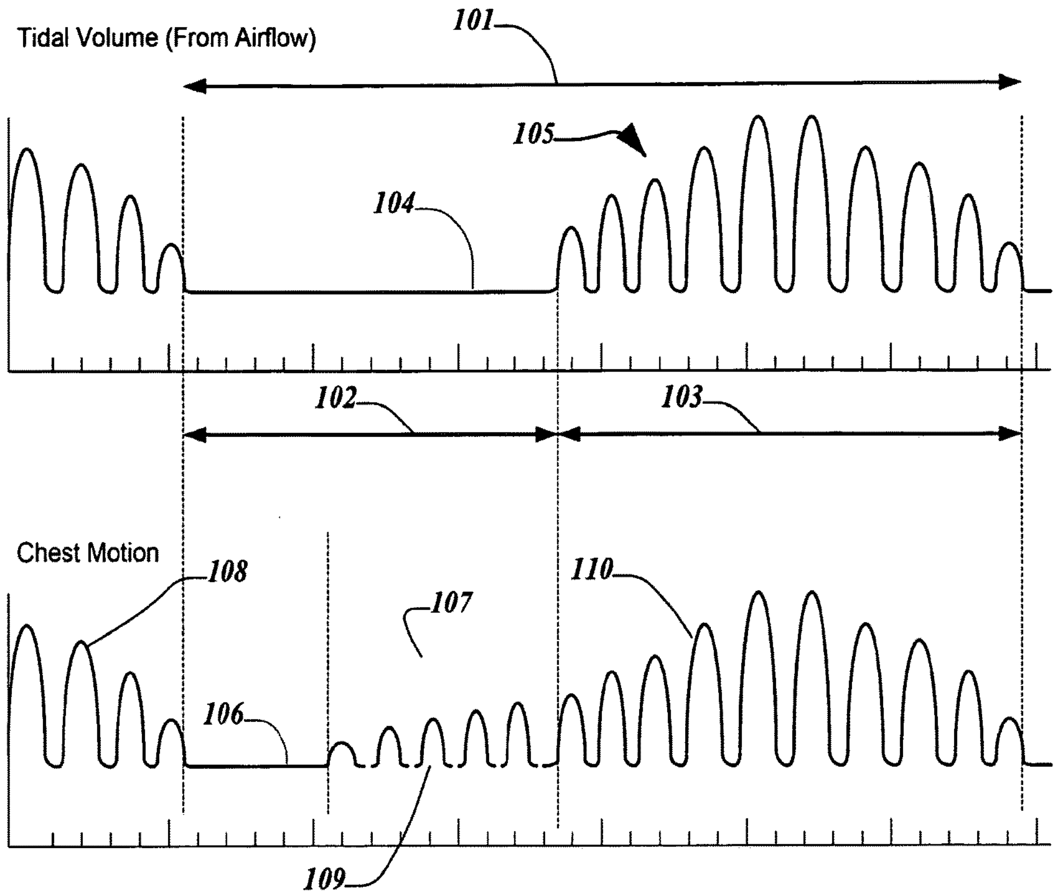

Tidal Volume (From Airflow)
101
105
104
102
103
Chest Motion
108
107
110
106
109

Figure 2

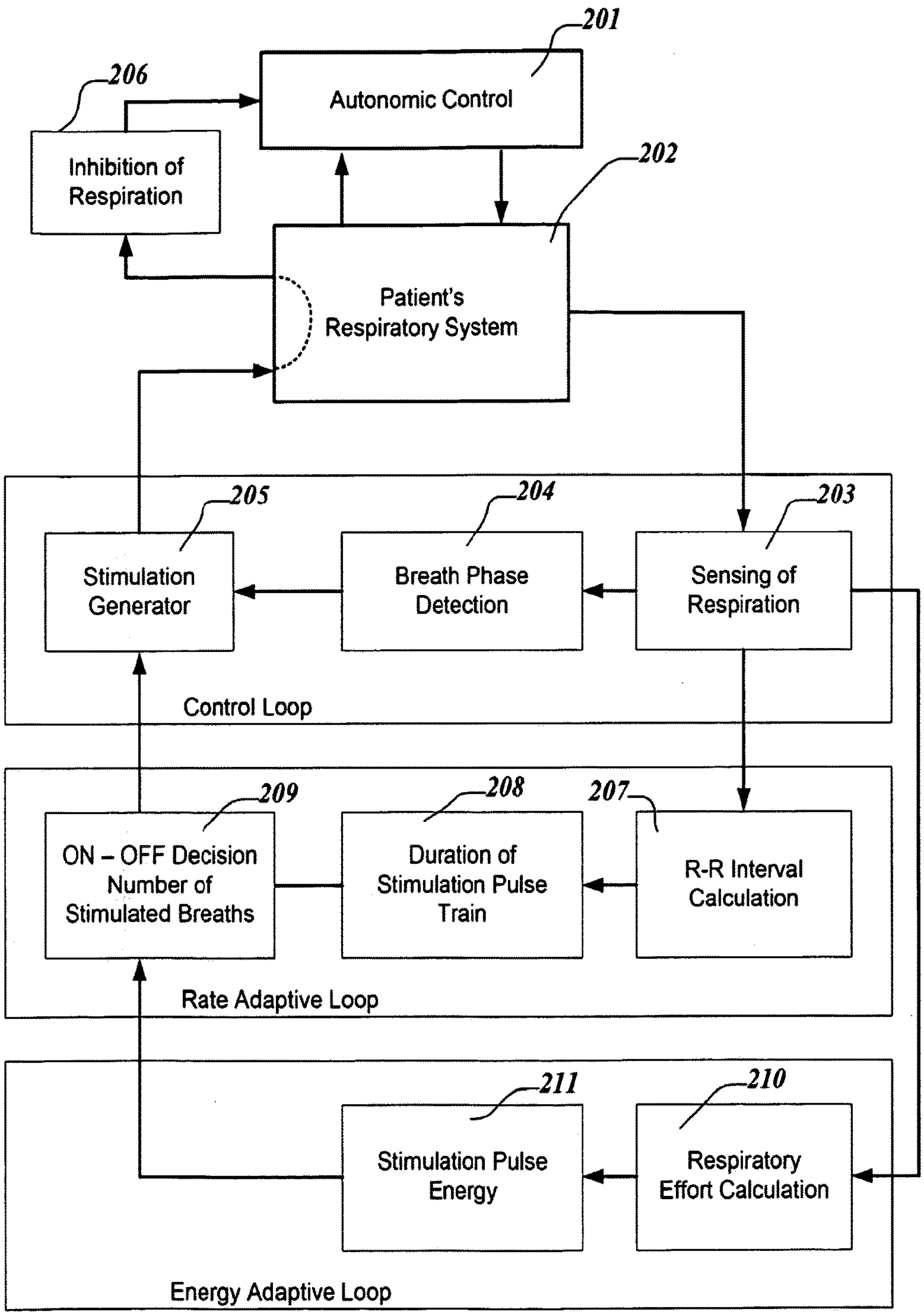
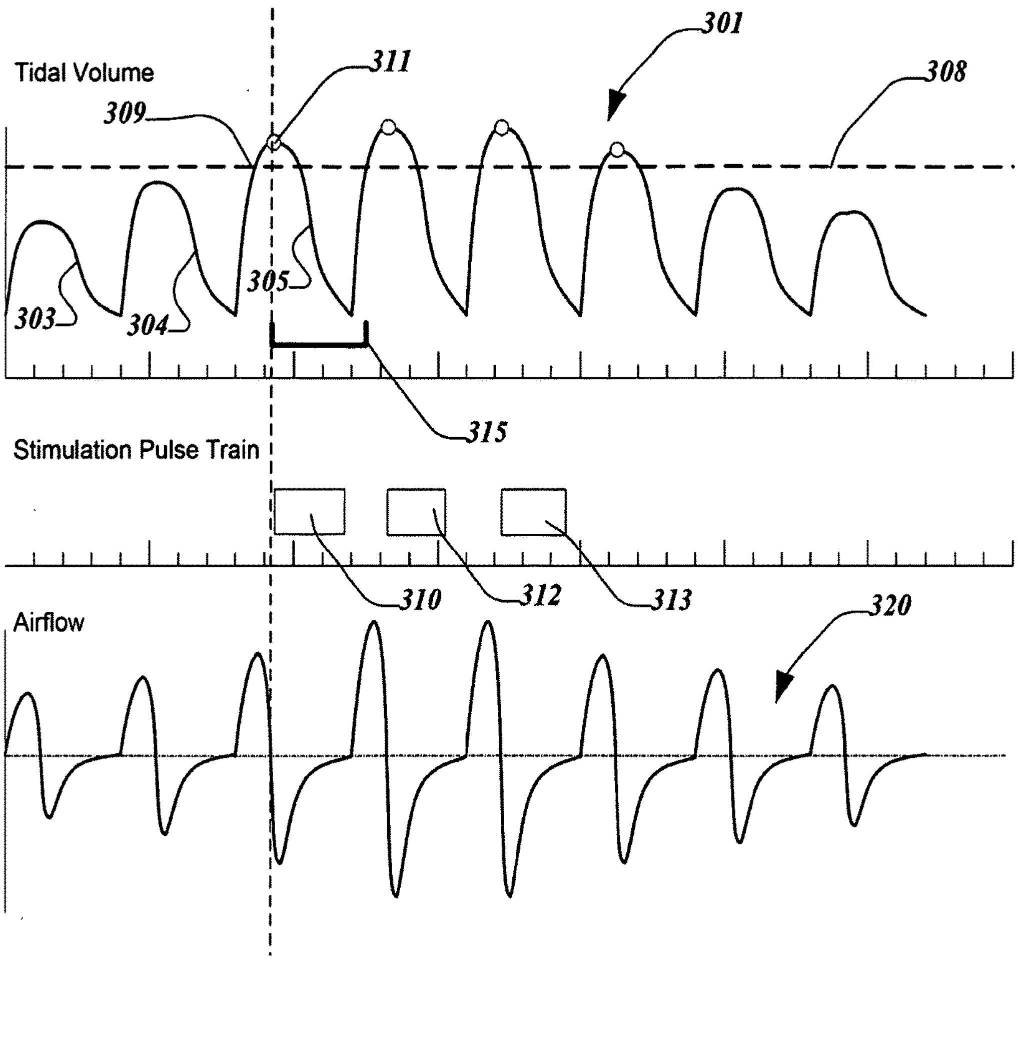
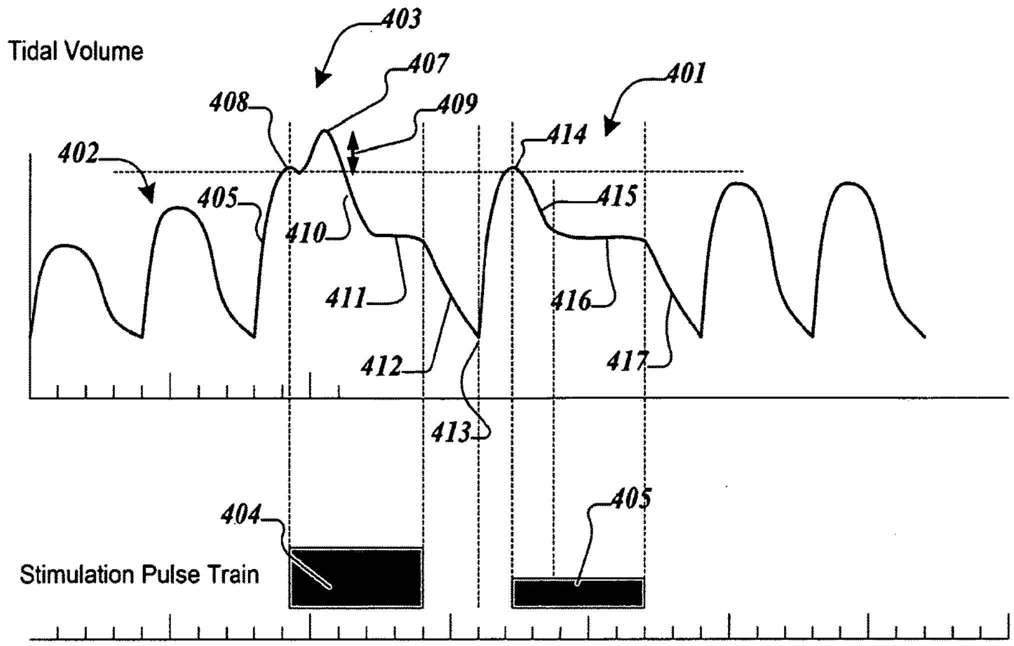

201
Autonomic Control
206
Inhibition of Respiration
202
Patient's Respiratory System
205
Stimulation Generator
204
Breath Phase Detection
203
Sensing of Respiration
Control Loop
209
ON – OFF Decision Number of Stimulated Breaths
208
Duration of Stimulation Pulse Train
207
R-R Interval Calculation
Rate Adaptive Loop
211
Stimulation Pulse Energy
210
Respiratory Effort Calculation
Energy Adaptive Loop

Figure 3



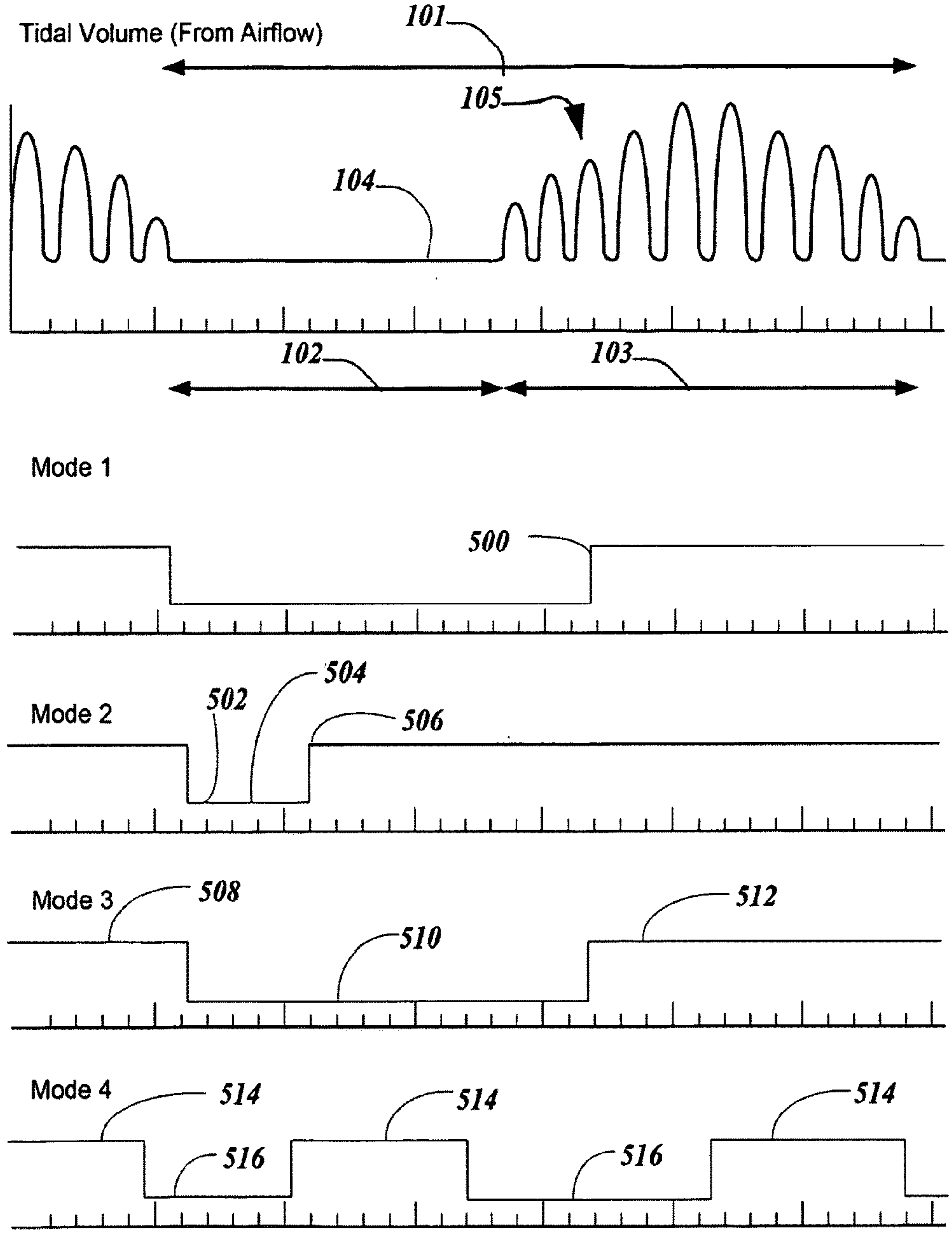
Tidal Volume
301
311
308
309
303
304
305
315
Stimulation Pulse Train
310
312
313
Airflow
320

Figure 4



Tidal Volume
403
407
401
408
409
414
402
405
415
410
411
416
412
417
413
404
405
Stimulation Pulse Train

Figure 5



Tidal Volume (From Airflow)
101
105
104
102
103
Mode 1
500
Mode 2
502
504
506
Mode 3
508
510
512
Mode 4
514
516
514
516
514

Figure 6

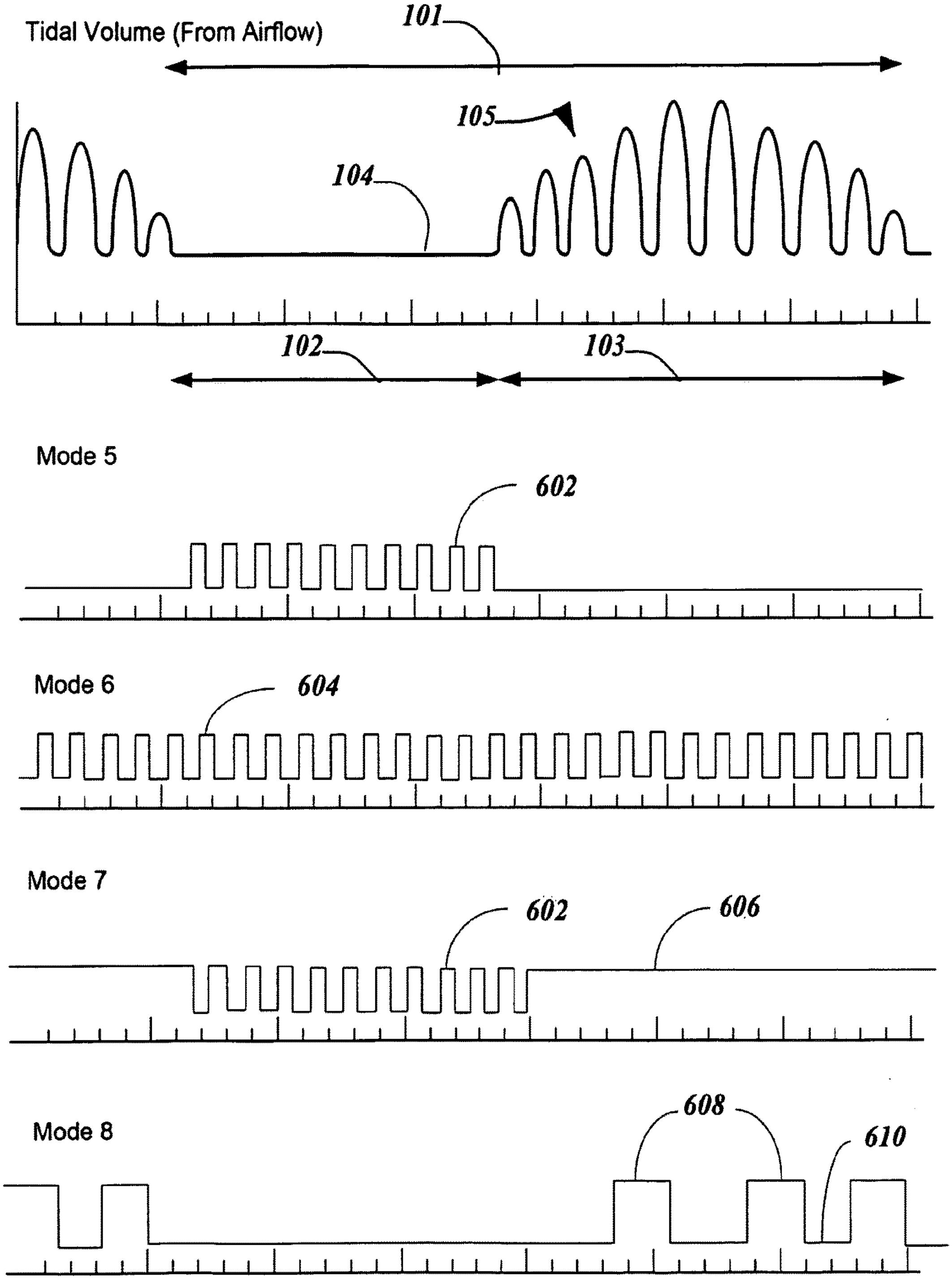

Tidal Volume (From Airflow)
101
105
104
102
103
Mode 5
602
Mode 6
604
Mode 7
602
606
Mode 8
608
610

Figure 7

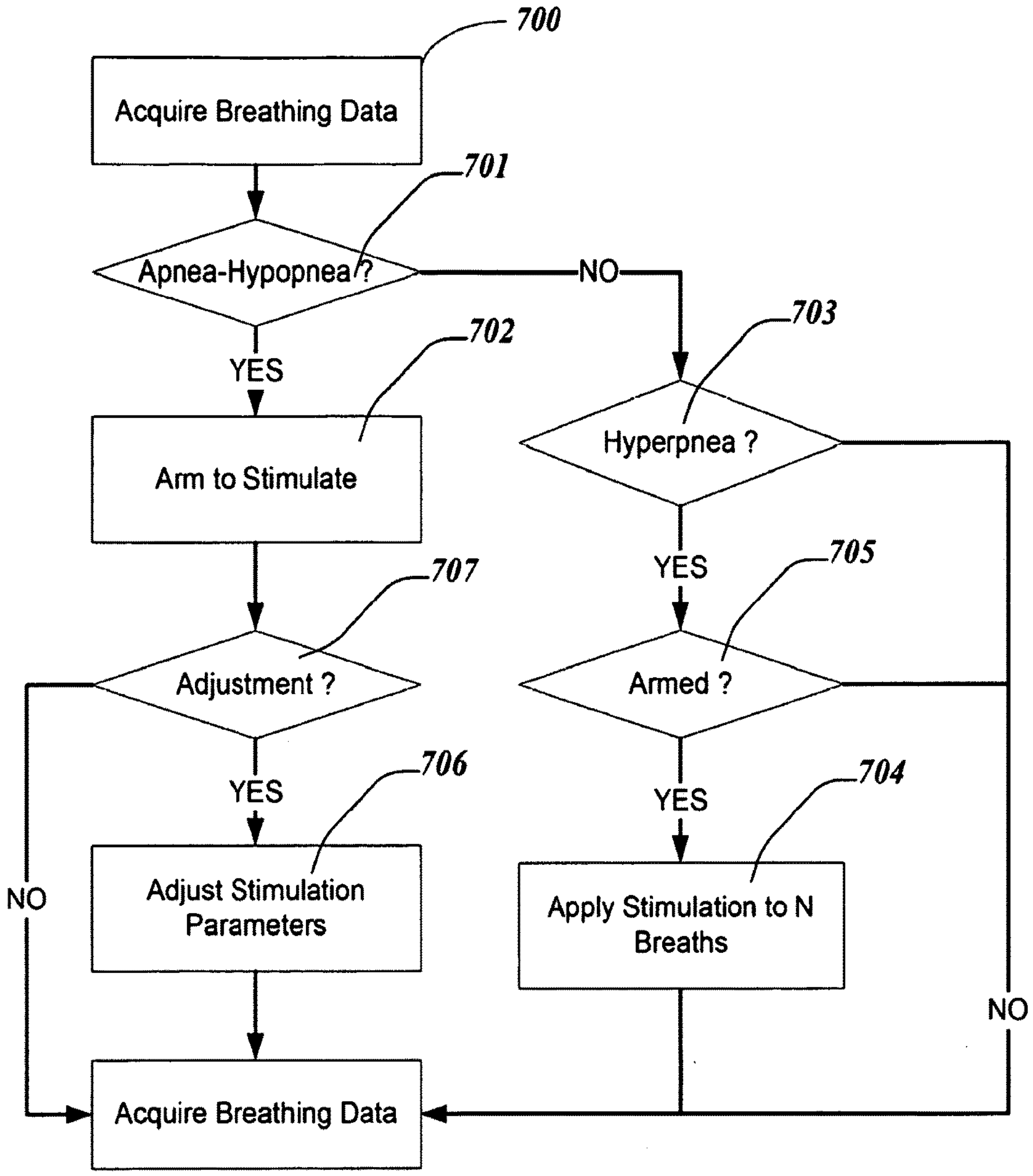

700
Acquire Breathing Data
701
Apnea-Hypopnea ?
NO
YES
702
Arm to Stimulate
703
Hyperpnea ?
YES
705
707
Adjustment ?
Armed ?
YES
706
YES
704
NO
Adjust Stimulation Parameters
Apply Stimulation to N Breaths
NO
Acquire Breathing Data

Figure 8

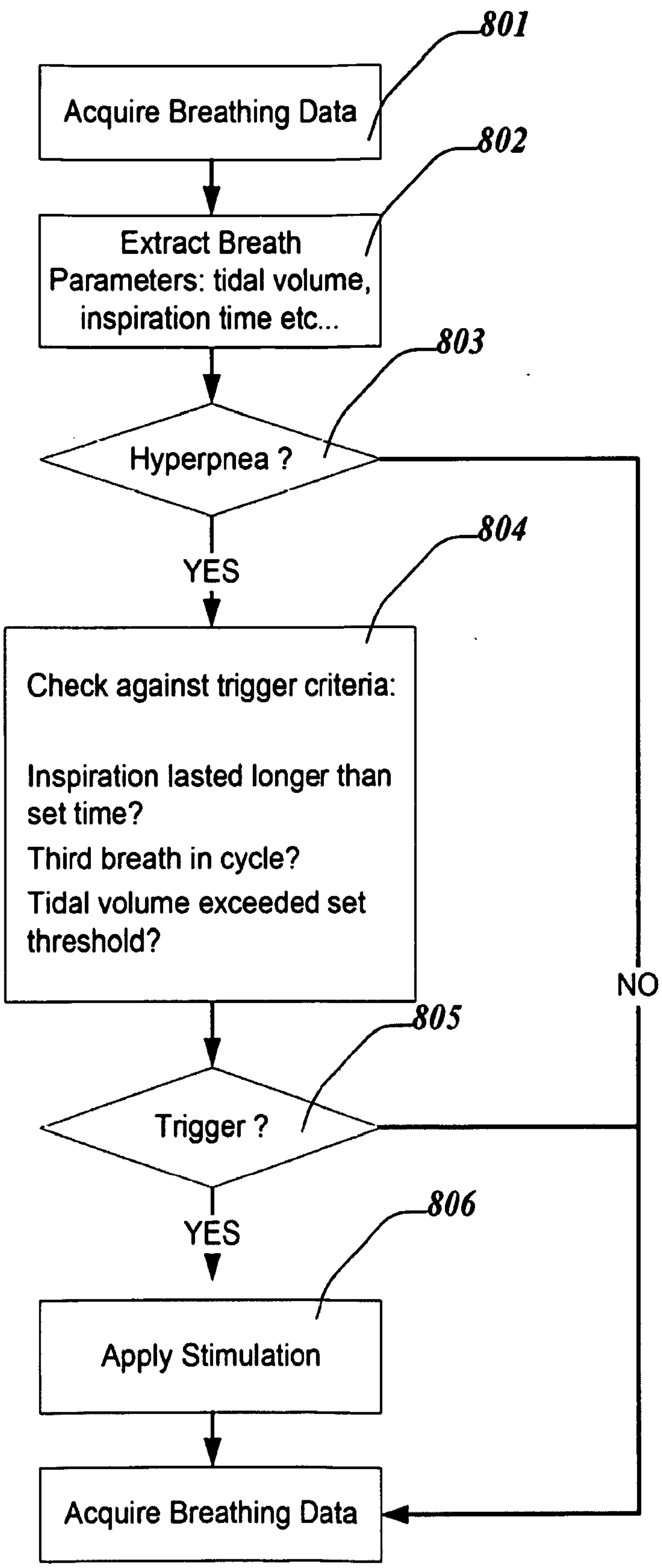

801
Acquire Breathing Data
802
Extract Breath Parameters: tidal volume, inspiration time etc...
803
Hyperpnea ?
YES
804
Check against trigger criteria:
Inspiration lasted longer than set time?
Third breath in cycle?
Tidal volume exceeded set threshold?
NO
805
Trigger ?
YES
806
Apply Stimulation
Acquire Breathing Data

Figure 9

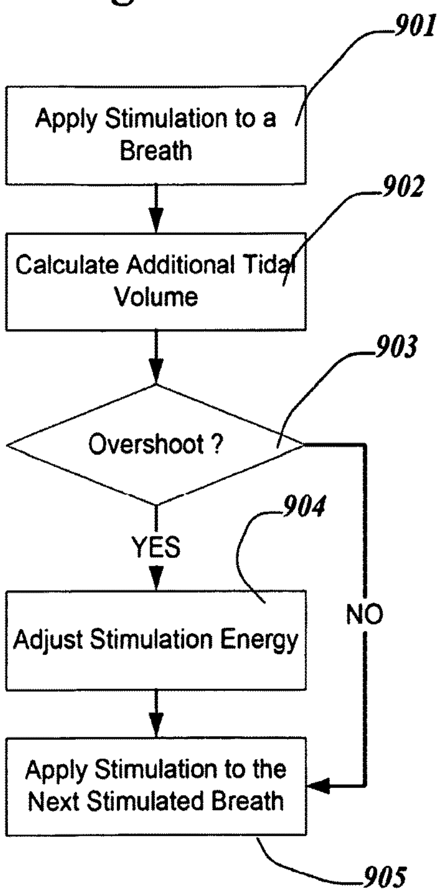


Figure 10

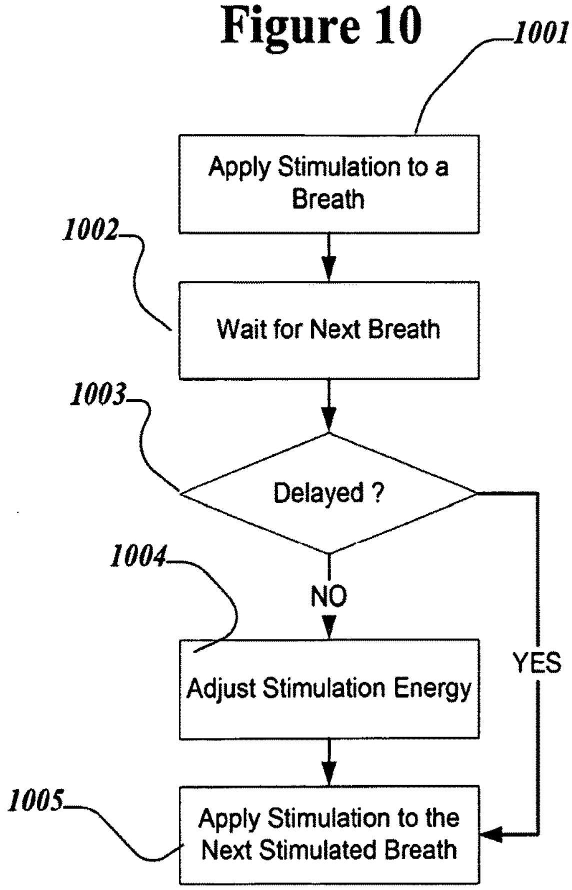


Figure 11

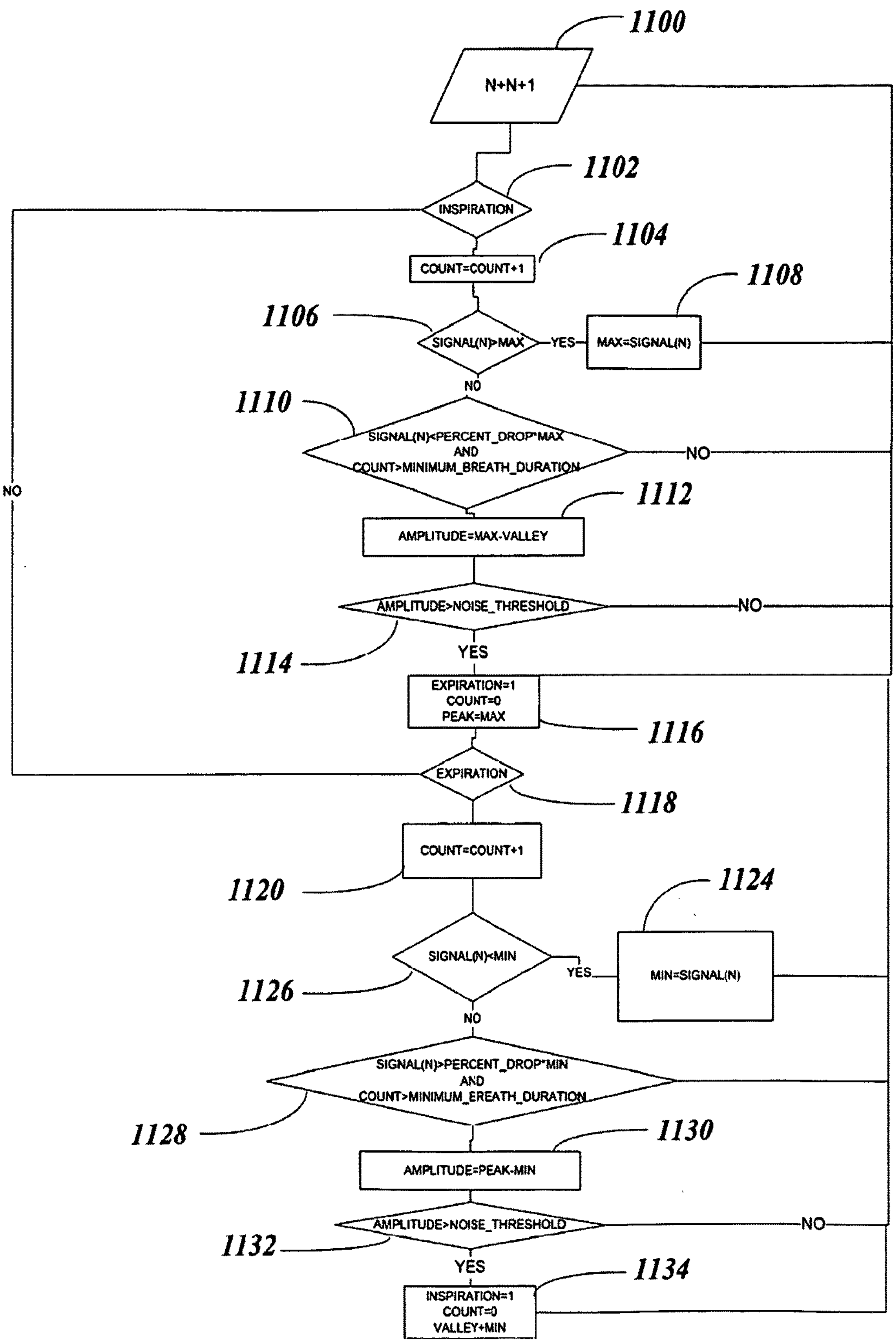

1100
N+N+1
1102
INSPIRATION
NO
1104
COUNT=COUNT+1
1106
SIGNAL(N)>MAX
YES
1108
MAX=SIGNAL(N)
NO
1110
SIGNAL(N)<PERCENT_DROP*MAX
AND
COUNT>MINIMUM_BREATH_DURATION
NO
1112
AMPLITUDE=MAX-VALLEY
AMPLITUDE>NOISE_THRESHOLD
NO
1114
YES
EXPIRATION=1
COUNT=0
PEAK=MAX
1116
EXPIRATION
1118
COUNT=COUNT+1
1120
1124
SIGNAL(N)<MIN
YES
MIN=SIGNAL(N)
1126
NO
SIGNAL(N)>PERCENT_DROP*MIN
AND
COUNT>MINIMUM_EREATH_DURATION
1128
1130
AMPLITUDE=PEAK-MIN
AMPLITUDE>NOISE_THRESHOLD
NO
1132
YES
1134
INSPIRATION=1
COUNT=0
VALLEY+MIN

Figure 12

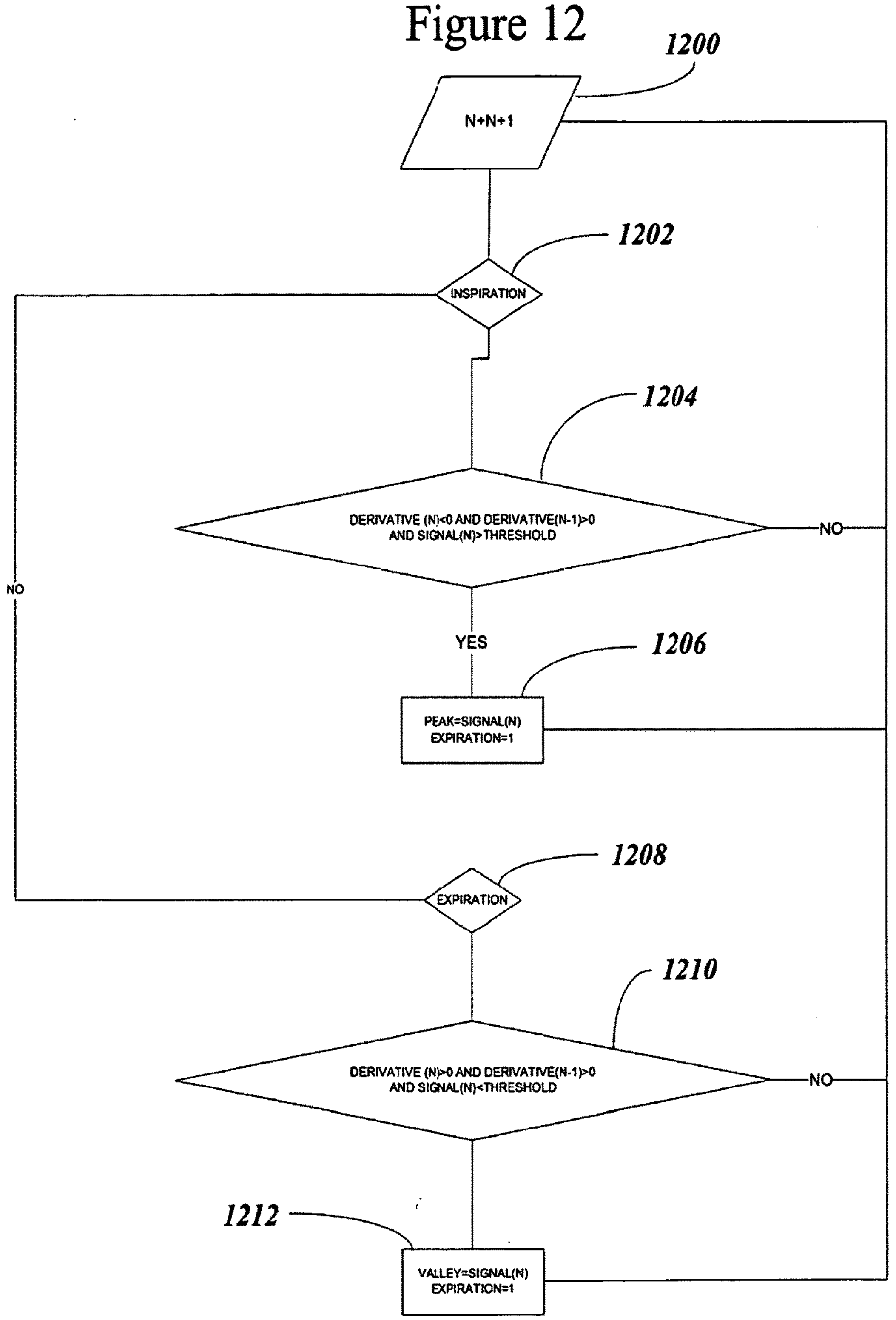

1200
N+N+1
1202
INSPIRATION
1204
DERIVATIVE (N)<0 AND DERIVATIVE(N-1)>0
AND SIGNAL(N)>THRESHOLD
NO
NO
YES
1206
PEAK=SIGNAL(N)
EXPIRATION=1
1208
EXPIRATION
1210
DERIVATIVE (N)>0 AND DERIVATIVE(N-1)>0
AND SIGNAL(N)<THRESHOLD
NO
1212
VALLEY=SIGNAL(N)
EXPIRATION=1

Figure 13

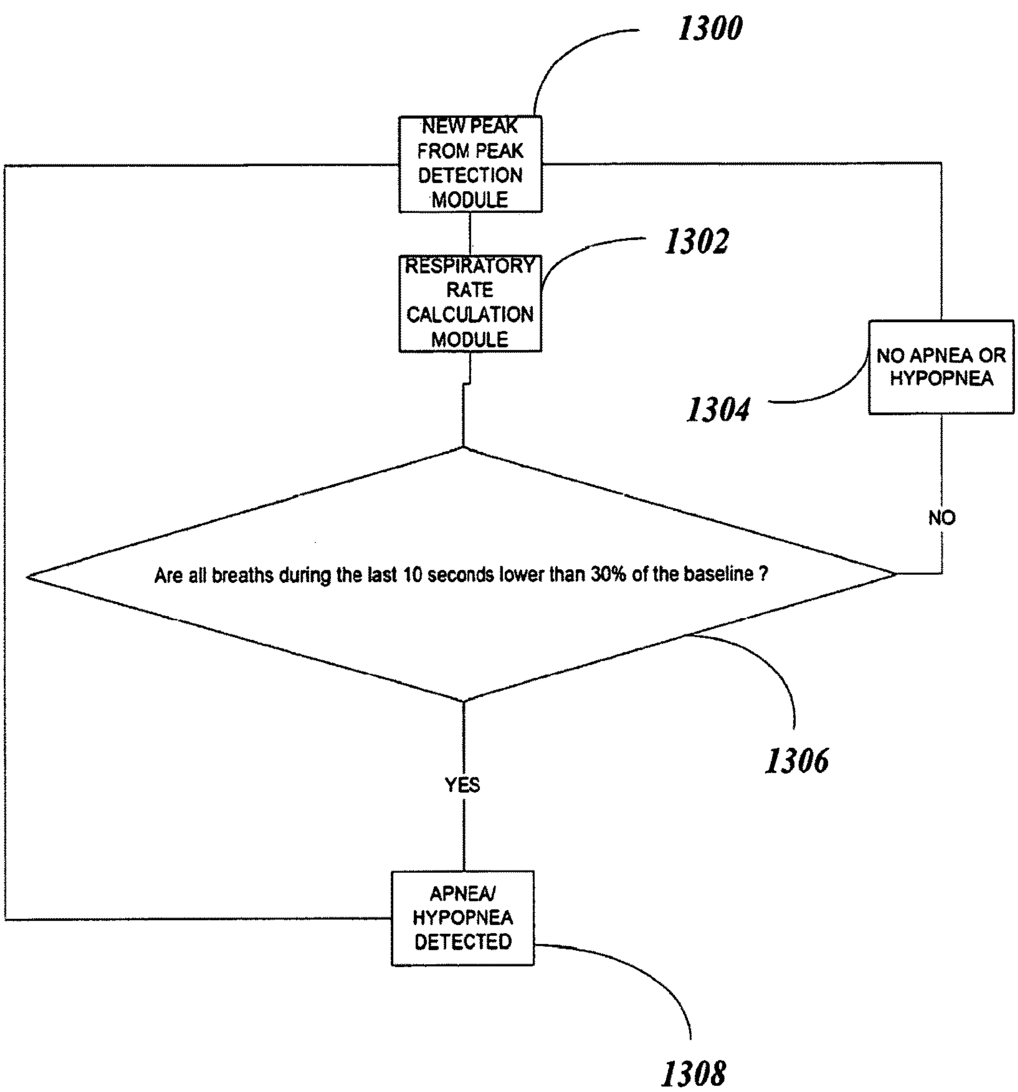

1300
NEW PEAK FROM PEAK DETECTION MODULE
1302
RESPIRATORY RATE CALCULATION MODULE
NO APNEA OR HYPOPNEA
1304
NO
Are all breaths during the last 10 seconds lower than 30% of the baseline ?
1306
YES
APNEA/ HYPOPNEA DETECTED
1308

Figure 14

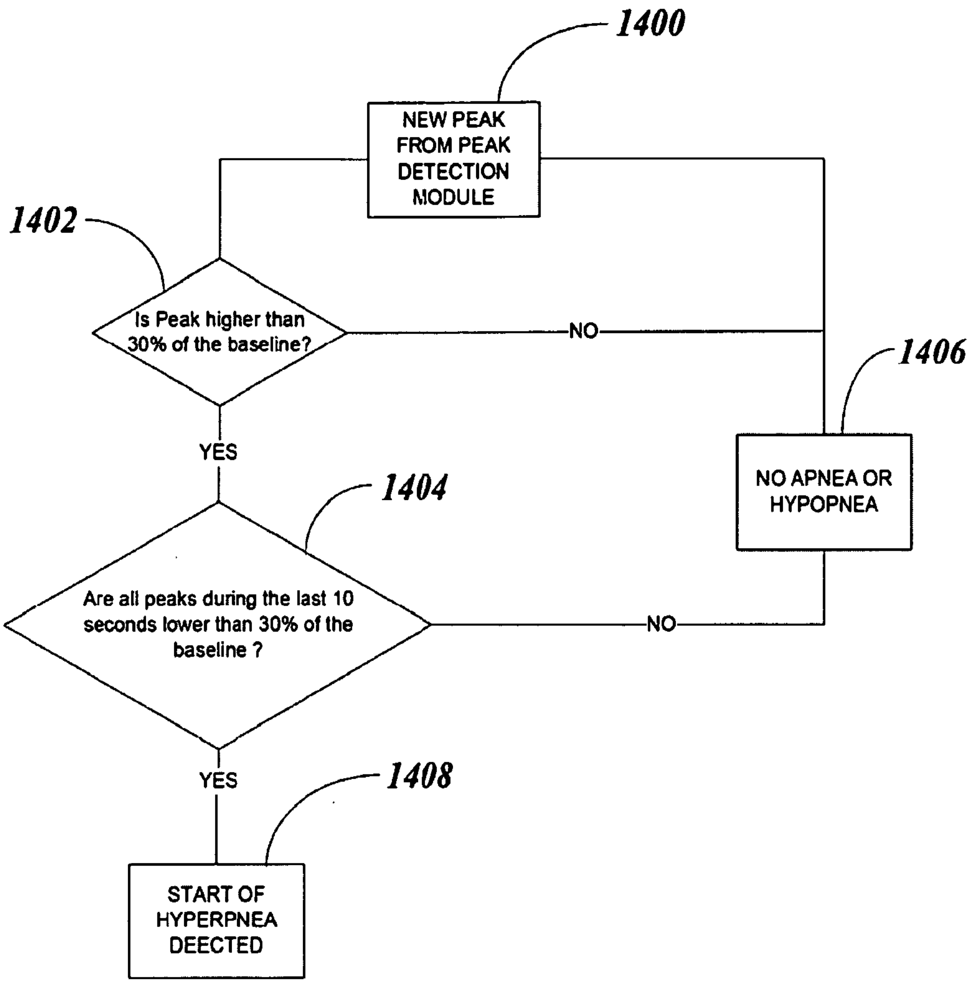

1400
NEW PEAK FROM PEAK DETECTION MODULE
1402
Is Peak higher than 30% of the baseline?
NO
YES
1404
Are all peaks during the last 10 seconds lower than 30% of the baseline ?
NO
1406
NO APNEA OR HYPOPNEA
YES
1408
START OF HYPERPNEA DEECTED

Figure 15

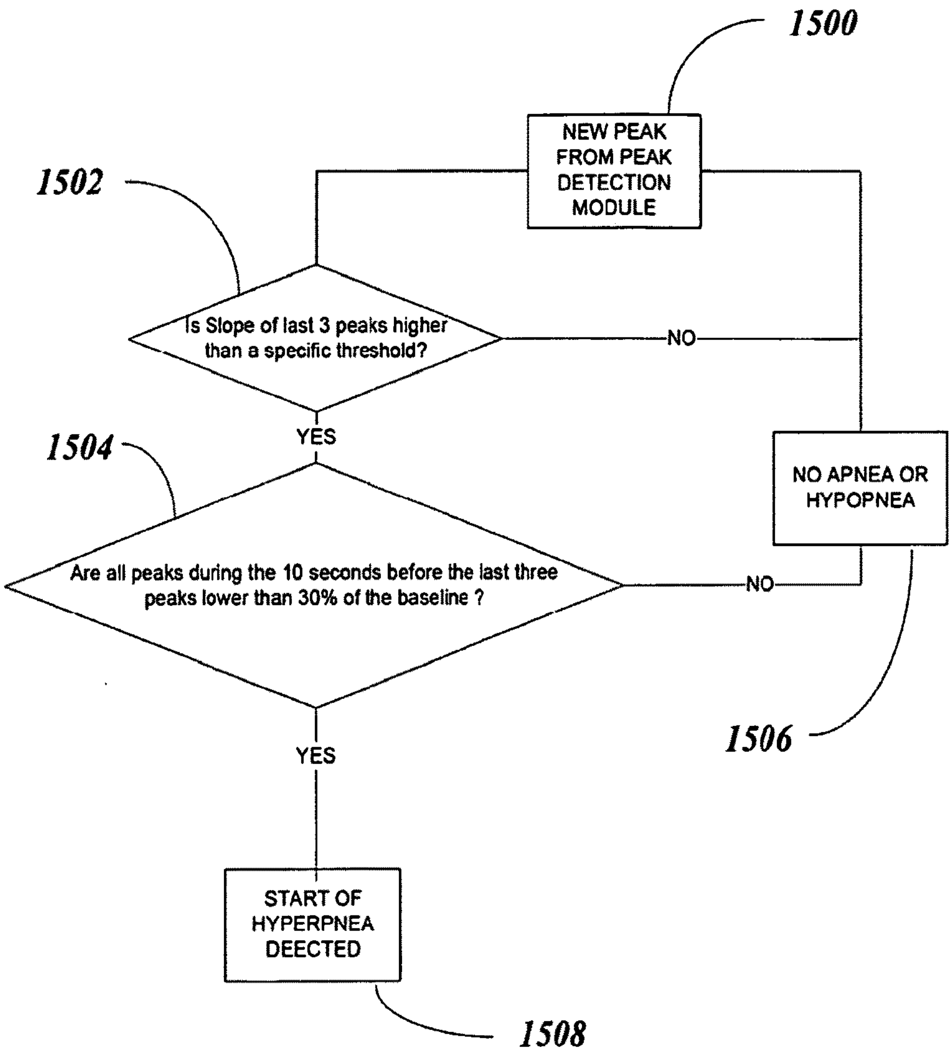

1500
NEW PEAK FROM PEAK DETECTION MODULE
1502
Is Slope of last 3 peaks higher than a specific threshold?
NO
YES
1504
Are all peaks during the 10 seconds before the last three peaks lower than 30% of the baseline ?
NO
NO APNEA OR HYPOPNEA
1506
YES
START OF HYPERPNEA DEECTED
1508

Figure 16

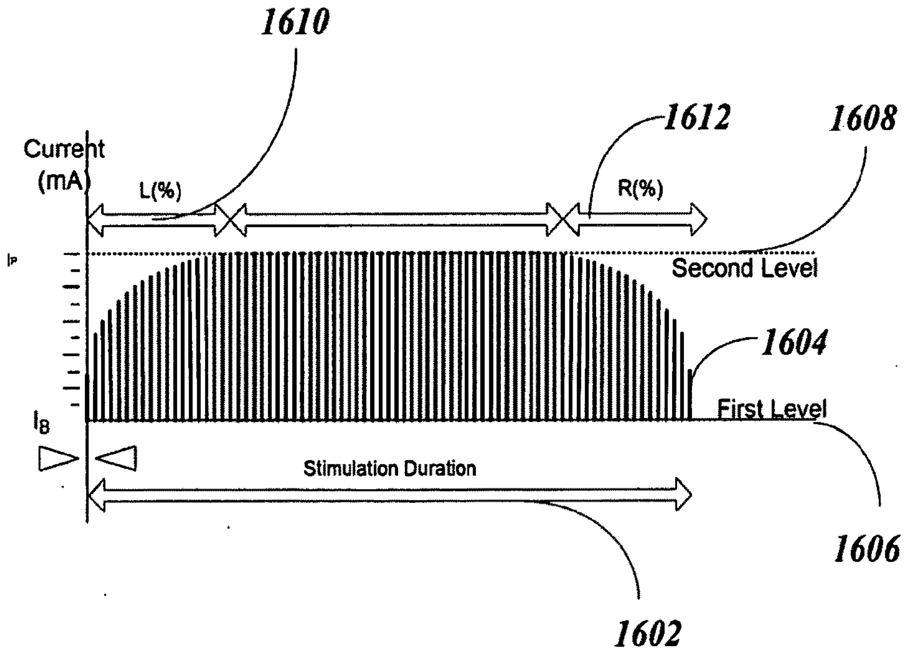

1610
1612
1608
Current
(mA)
L(%)
R(%)
IP
Second Level
1604
First Level
IB
Stimulation Duration
1606
1602

Figure 17

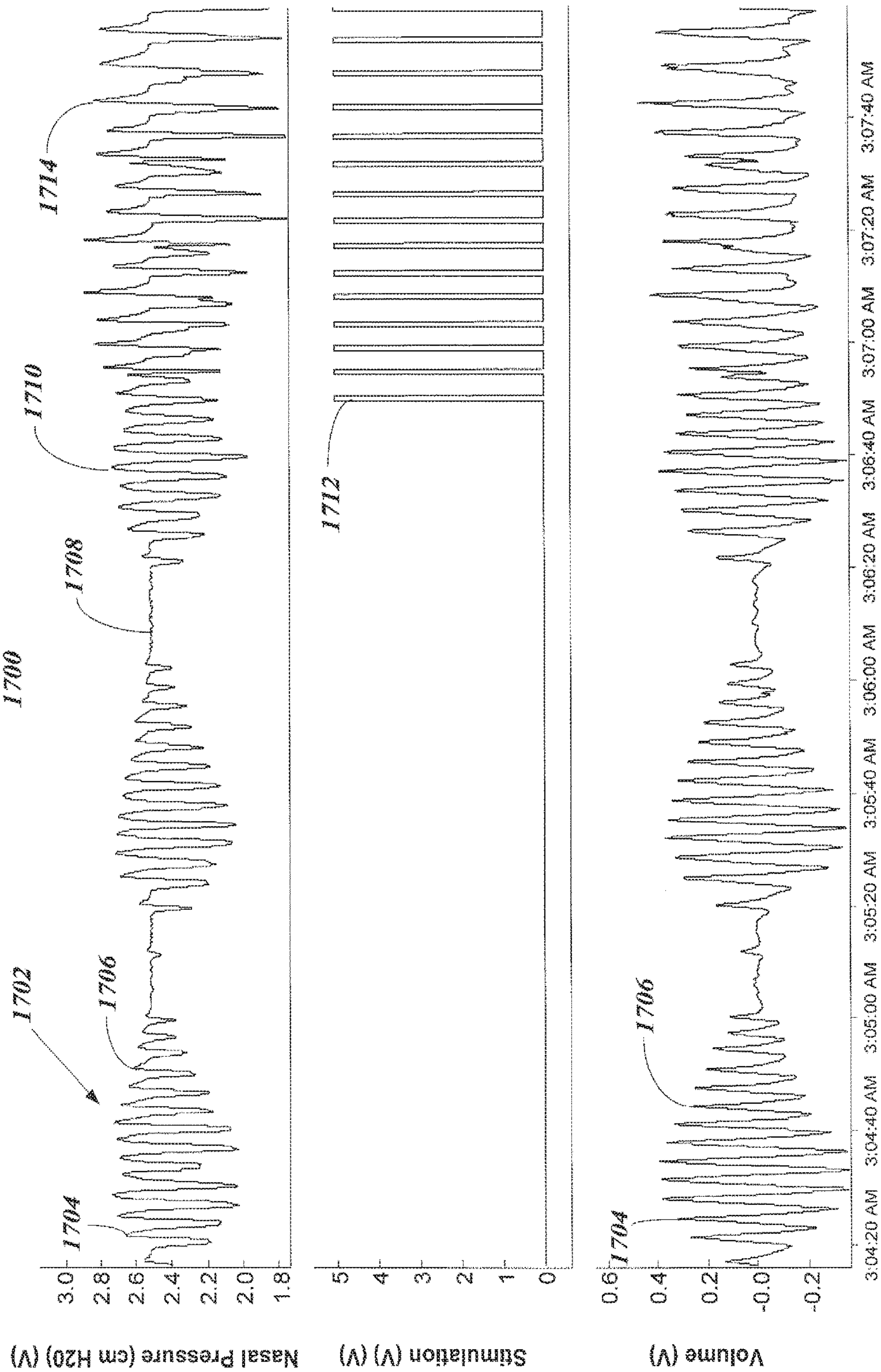
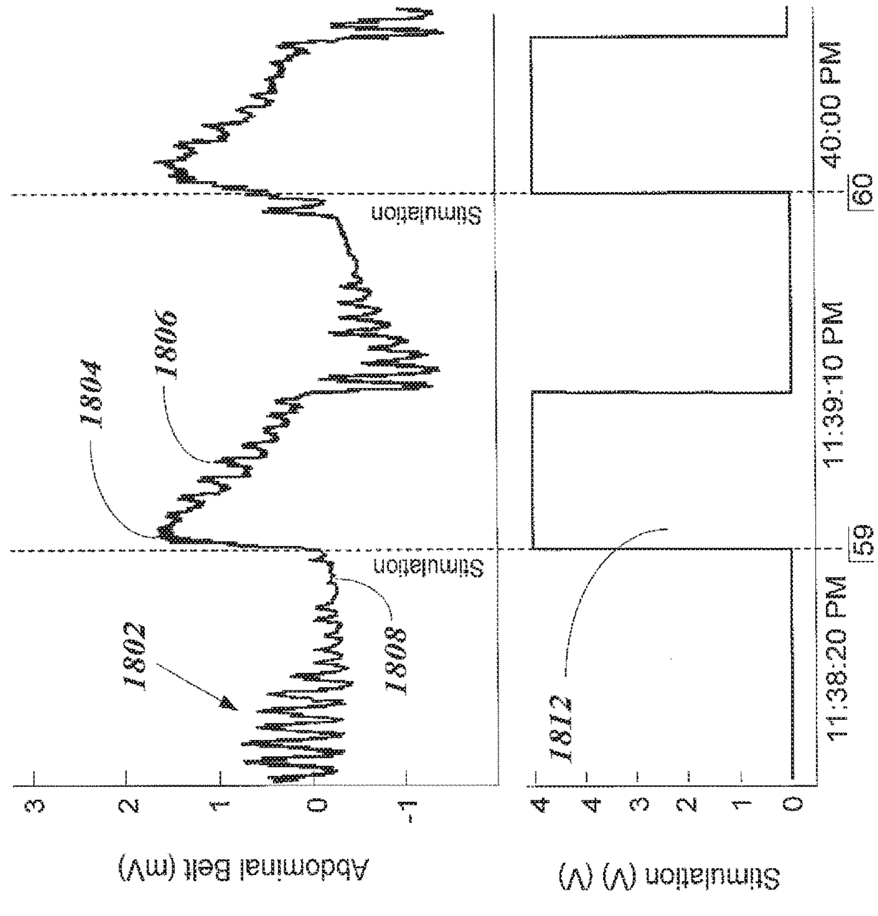

1700
1702
1704
1706
1708
1710
1712
1714
Nasal Pressure (cm H20) (V)
Stimulation (V) (V)
Volume (V)
3:04:20 AM
3:04:40 AM
3:05:00 AM
3:05:20 AM
3:05:40 AM
3:06:00 AM
3:06:20 AM
3:06:40 AM
3:07:00 AM
3:07:20 AM
3:07:40 AM

Figure 18


Abdominal Belt (mV)
3
2
1
0
-1
1802
1804
1806
1808
Stimulation
Stimulation
Stimulation (V) (V)
4
4
3
2
1
0
1812
11:38:20 PM
59
11:39:10 PM
60
40:00 PM

DETECTING AND TREATING DISORDERED BREATHING

CROSS REFERENCE TO RELATED CASES

[0001] The present application claims priority to U.S. Provisional Application entitled "ALGORITHMS FOR PHRENIC NERVE STIMULATION" filed Jun. 27, 2007, Ser. No. 60/937,426. Applicant claims the benefit of the filing date of the provisional application and hereby incorporates the provisional application herein in relevant part.

FIELD OF THE INVENTION

[0002] The present invention relates to detecting and treating defects in human respiration, particularly the types of disordered breathing that may accompany heart disease.

BACKGROUND

[0003] Human respiration is an extraordinarily complicated process. Although rhythmic breathing, inhalation and exhalation, is familiar to all of us, the underlying processes that give rise to the observed respiration cycle are complex. In general respiration permits gas exchange between gases in the blood and gases in the environment. In a healthy individual, oxygen is provided to the blood and carbon dioxide, which is a product of metabolic processes in the body, is driven off into the atmosphere. Respiration is subject to both voluntary and involuntary control and several disease processes can have a profound impact on respiration.

[0004] A person's respiration is controlled by the autonomic nervous system that integrates inputs from many physiologic sensors such as mechanoreceptors and chemoreceptors. The central nervous system commands the diaphragm and other muscles in the chest as well as in the neck to phasically contract and relax thus producing a breath of certain shape and tidal volume. It also acts as a respiratory pacemaker by setting the breathing rate. In a normal sleeping person the next breath is typically initiated substantially immediately after the previous breath is completely exhaled. The term tidal volume refers to the volume of air inspired or expired during a respiratory cycle. Together tidal volume and breathing rate determine minute volume of ventilation that determines the rate at which oxygen is delivered and CO_2 is removed from the respiratory system.

[0005] The term disordered breathing is used herein to describe a variety of observable respiration patterns that deviate from normal respiration. For example, Cheyne-Stokes respiration ("CSR") is clinically observed and declared when a patient has bouts of "rapid" and/or "deep" breathing followed by reductions in breathing or apnea-hypopnea. This abnormal pattern of breathing can be seen in patients with strokes, traumatic brain injuries, brain tumors, and congestive heart failure and is usually a result of poor control of blood gas chemistry by the central nervous system.

[0006] "Pure" Cheyne-Stokes respiration is also called central sleep apnea by the medical community and is sometimes present with congestive heart failure. However, CSR breathing may be mixed with other respiration disorders that may or may not be related to congestive heart failure or other cardiac disorders.

SUMMARY

[0007] Embodiments in accordance with the present invention are directed to detecting and treating disordered breathing. In some embodiments, a device may operate by sensing natural respiration and phasically synchronizing the delivery of a stimulus with the breath after inspiration. The stimulation of these embodiments is provided to at least one half of a patient's phrenic nerves which innervate one side of the diaphragm associated with one lung. The stimulus is of a sufficient character to cause that lung to "be still," with some amount of air retained in the lung, and lung volume generally will not change during the stimulation, within some broadly defined limits. It is the belief of the inventors that it may be sufficient to stimulate and still only one lung under the theory that compensatory physiologic feedback mechanisms preserved on the unstimulated lung of the central and autonomic nervous system will interact in a virtuous and favorable way with the stimulation regime to provide the therapy.

[0008] It is believed that arresting at least one lung will prolong breaths and thus temporarily slow respiration and modify or modulate the tidal volume of breathing. This reduction of tidal volume may prevent blood carbon dioxide from being driven to low levels associated with apnea.

[0009] In other embodiments in accordance with the present invention, the stimulus is applied to still at least one lung upon detection of an apnea-hypopnea of some length or upon the detection of hyperpnea. In these embodiments, the stimulation may be initiated during the apnea-hypopnea period or upon detection of a breath of a predetermined intensity near the end of apnea-hypopnea. The stimulation may be initiated in phase with respiration or irrespective of the phase of respiration. If initiated irrespective of the phase of respiration, the stimulation may be gradually increased in intensity so as to expand and still at least one lung slowly so as not to disturb or arouse a sleeping patient. For purposes of this discussion, hyperpnea is defined as abnormally rapid or deep breathing. In some but not all cases, hyperpnea may involve rapid breathing that is compensating for the reduced respiratory effectiveness of a previous period of apnea-hypopnea or reduced breathing.

[0010] Embodiments in accordance with the present invention may cooperate with naturally occurring physiologic feedback mechanisms to provide a therapy for disordered breathing. In one embodiment, a fully implanted device coupled to a transvenous lead system may be provided to monitor breathing and extract inspiration points, expiration points and other data associated with a physiologic breathing pattern. A programmable computer may be provided with control software for managing both the respiration measuring system as well as extracting useful data concerning breathing. The programmable computer may be described as a combination of circuitry and software, circuitry and firmware, or a computer with software or firmware, and all of these descriptions contemplate the same essential elements. The control software within the device may select the timing for the delivery of hemi diaphragmatic stimulation and accept input information from a variety of sources that can be used in nested control loops to tailor the therapy to a particular patient and to provide a different therapy as the patient's needs change.

[0011] In one embodiment in accordance with the invention, a system for treating disordered breathing includes a stimulation lead having a stimulation electrode, a respiration

sensor, an energy source, a pulse generator, and circuitry. In this embodiment, the circuitry is operative to monitor signals from the respiration sensor and detect apnea-hypopnea. The circuitry will deliver a stimulation signal to the stimulation electrode after the detection of apnea-hypopnea. In this embodiment, the stimulation signal has a duration of at least ten seconds.

[0012] In another embodiment in accordance with the invention, a system for treating disordered breathing includes a stimulation lead having stimulation electrode, a respiration sensor, an energy source, a pulse generator, and circuitry. In this embodiment, the circuitry is operative to monitor signals from the respiration sensor and detect apnea-hypopnea. The circuitry will deliver a stimulation pulse to the stimulation electrode after the detection of a hyperpnea following apnea-hypopnea. In this embodiment, the stimulation signal has a duration of at least ten seconds.

[0013] In yet another embodiment in accordance with the invention, a system for treating disordered breathing includes a stimulation lead having a stimulation electrode, a respiration sensor, an energy source, a pulse generator, and circuitry. In this embodiment, the circuitry is operative to monitor signals from the respiration sensor and detect apnea-hypopnea by accumulating data from the respiration sensor to determine a value representative of average tidal volume and then detecting hyperpnea when, for example, the measured value is below 30% of the average value for ten seconds. The circuitry will deliver a stimulation pulse to the stimulation electrode after the detection of apnea-hypopnea. In this embodiment, the stimulation signal has a duration of at least ten seconds.

[0014] In yet another embodiment in accordance with the invention, a system for treating disordered breathing includes a stimulation lead having a stimulation electrode, a respiration sensor, an energy source, a pulse generator, and circuitry. In this embodiment, the circuitry is operative to monitor signals from the respiration sensor and detect apnea-hypopnea by accumulating data from the respiration sensor to determine a value representative of average tidal volume and then detecting hyperpnea when the measured value is below 30% of the average value for ten seconds. The circuitry will then detect hyperpnea when the value representative of tidal volume exceeds 30% of the average value after the detection of apnea-hypopnea. The circuitry will deliver a stimulation pulse to the stimulation electrode after the detection of hyperpnea following apnea-hypopnea. In this embodiment, the stimulation signal has a duration of at least ten seconds.

[0015] In another embodiment in accordance with the invention, a system for treating disordered breathing includes a stimulation lead having a stimulation electrode, a respiration sensor, an energy source, a pulse generator, and circuitry. In this embodiment the stimulation lead is configured to be implanted in a blood vessel proximate a phrenic nerve in a patient. In this embodiment, the circuitry is operative to monitor signals from the respiration sensor and detect apnea-hypopnea. The circuitry will deliver a stimulation pulse to the stimulation electrode after the detection of apnea-hypopnea. In this embodiment, the stimulation signal has a duration of at least ten seconds.

[0016] A system for treating disordered breathing in accordance with embodiments of the invention includes a stimulation lead having a stimulation electrode, a respiration sensor, an energy source, a pulse generator, and circuitry. The circuitry of this embodiment is operative to determine the onset of a hyperpnea based on the respiration sensor signals and deliver a stimulation signal to the stimulation electrode during hyperpnea, the signal having a duration of at least one second to extend the duration of the breath.

[0017] Another system for treating disordered breathing in accordance with embodiments of the invention includes a stimulation lead having a stimulation electrode, a respiration sensor, an energy source, a pulse generator, and circuitry. The system receives signals from the respiration sensor and calculates a baseline breath duration. The circuitry of this embodiment is operative to determine the onset of a hyperpnea based on the respiration sensor signals and deliver a stimulation signal to the stimulation electrode during hyperpnea, the signal having a duration of at least 25% of the baseline breath duration.

[0018] Another system for treating disordered breathing in accordance with embodiments of the invention includes a stimulation lead having a stimulation electrode, a respiration sensor, an energy source, a pulse generator, and circuitry. The circuitry of this embodiment is operative to determine the onset of a hyperpnea and the peak of inspiration based on the respiration sensor signals and deliver a stimulation signal to the stimulation electrode during hyperpnea proximate the peak of inspiration, the signal having a duration of at least one second to extend the duration of the breath.

[0019] A system for treating disordered breathing in accordance with embodiments of the invention includes a stimulation lead having a stimulation electrode, a respiration sensor, an energy source, a pulse generator, and circuitry. The circuitry of this embodiment is operative to determine the onset of a hyperpnea based on the respiration sensor signals and to determine the duration of a hyperpnea cycle and deliver a stimulation signal to the stimulation electrode during hyperpnea, the signal having a duration greater than 25% of the duration of the hyperpnea cycle.

[0020] Another system for treating disordered breathing in accordance with embodiments of the invention includes a stimulation lead having a stimulation electrode, a respiration sensor, an energy source, a pulse generator, and circuitry. The circuitry of this embodiment is operative to determine the onset of a hyperpnea based on the respiration sensor signals and to determine the duration of a hyperpnea cycle. The circuitry is also operative to deliver a stimulation signal to the stimulation electrode during hyperpnea, the signal being initiated after the midpoint of the hyperpnea cycle and having a duration of at least one second to extend the duration of the breath. In some variations of this embodiment the signal is initiated proximate the peak of inspiration of a breath that occurs after the midpoint of hyperpnea.

[0021] Another system for treating disordered breathing in accordance with embodiments of the invention includes a stimulation lead having a stimulation electrode, a respiration sensor, an energy source, a pulse generator, and circuitry. The circuitry of this embodiment is operative to determine the onset of a hyperpnea based on the respiration sensor signals and to determine the duration of a hyperpnea cycle. The circuitry is also operative to deliver a stimulation signal to the stimulation electrode during hyperpnea, the signal being initiated after the midpoint of the hyperpnea cycle and having a duration of at least one second to extend the duration of the breath. The circuitry of this embodiment is also operative to deliver a stimulation signal at the peak of inspiration for several breaths beginning after the midpoint of hyperpnea.

[0022] Another system for treating disordered breathing in accordance with embodiments of the invention includes a stimulation lead having a stimulation electrode, a respiration sensor, an energy source, a pulse generator, and circuitry. The circuitry of this embodiment is operative to determine the onset of a hyperpnea based on the respiration sensor signals. The circuitry is also operative to deliver at least three segmented stimulation signals to the stimulation electrode during the hyperpnea.

[0023] Another system for treating disordered breathing in accordance with embodiments of the invention includes a stimulation lead having a stimulation electrode, a respiration sensor, an energy source, a pulse generator, and circuitry. The circuitry of this embodiment is operative to determine the onset of a hyperpnea based on the respiration sensor signals and to determine the average duration of a hyperpnea cycle and the average duration of an apnea-hypopnea cycle. The circuitry is also operative to deliver a stimulation signal to the stimulation electrode during hyperpnea based on the average duration of a hyperpnea cycle and establish a blanking period based on the average duration of an apnea-hypopnea cycle.

[0024] A system for treating disordered breathing in accordance with embodiments of the invention includes a stimulation lead having a stimulation electrode, a respiration sensor, an energy source, a pulse generator, and circuitry. The circuitry of this embodiment is operative to determine the onset of a hyperpnea based on the respiration sensor signals and deliver a stimulation signal to the stimulation electrode during hyperpnea, where the signal has a duration of at least one second and is in the form of a gradually rising and descending pulse train envelope.

[0025] In another embodiment in accordance with the invention, a method of monitoring or treating disordered breathing includes calculating an average duration of a patient's hyperpnea over some period of time and stimulating a diaphragm of the patient upon detection of hyperpnea. In this embodiment the stimulation lasts at least 30% as long as the calculated average duration of hyperpnea.

[0026] Another embodiment in accordance with the invention involves a method of monitoring or treating disordered breathing. The method includes gathering data related to a patient's breathing and generating a value representative of the tidal volume of the breaths of the patient. The tidal volumes of sequential breaths are compared and hyperpnea is detected when there are three sequential breaths where the tidal volume of each breath is at least 20% greater than the tidal volume of the previous breath. The method of this embodiment includes calculating an average duration of a patient's hyperpnea over some period of time and stimulating a diaphragm of the patient upon detection of hyperpnea. In this embodiment the stimulation lasts at least 30% as long as the calculated average duration of hyperpnea.

[0027] In another embodiment in accordance with the invention, a method of monitoring or treating disordered breathing includes calculating an average duration of a patient's hyperpnea over some period of time and stimulating a diaphragm of the patient upon detection of hyperpnea. In this embodiment the stimulation lasts at least 30% as long as the calculated average duration of hyperpnea. The stimulation signal of this embodiment is in the form of a gradually rising and descending pulse train envelope. Some examples of possible pulse train shapes include linear, parabolic, and elliptical.

[0028] In yet another embodiment in accordance with the invention, a method of monitoring or treating disordered includes calculating an average duration of a patient's episodes of hyperpnea over some period of time and an average midpoint of the hyperpnea episode and stimulating a diaphragm of the patient during hyperpnea after the midpoint of the hyperpnea.

[0029] In yet another embodiment in accordance with the invention, a method of monitoring or treating disordered includes calculating an average duration of a patient's episodes of hyperpnea over some period of time and an average midpoint of the hyperpnea episode and stimulating a diaphragm of the patient during hyperpnea after the midpoint of the hyperpnea. This embodiment includes determining the peak of inspiration and stimulating proximate the peak of inspiration.

[0030] In yet another embodiment in accordance with the invention, a method of monitoring or treating disordered includes calculating an average duration of a patient's episodes of hyperpnea over some period of time and an average midpoint of the hyperpnea episode and stimulating a diaphragm of the patient during hyperpnea after the midpoint of the hyperpnea. In this embodiment additional future breaths extending beyond the normal duration of hyperpnea are stimulated.

DETAILED DESCRIPTION

[0031] Turning now to the Figures, FIG. **1** is a stylized representation of tidal volume and chest motion over time of a patient suffering from mixed apnea within Cheyne-Stokes Respiration. The CSR cycle **101** consists of an apnea-hypopnea period **102** and a hyperpnea period **103**. During apnea-hypopnea **102** there is substantially no airflow **104** inspired or expired. During hyperpnea **103** airflow gradually increases, crests and then decreases from breath to breath. This pattern is often described as a crescendo-decrescendo pattern. In the beginning of apnea-hypopnea **106** there is no respiratory drive from the autonomic nervous system of the patient and consequently no substantial diaphragm or chest motion. This is an example of true or pure central sleep apnea. It may be caused by the suppression of drive to breathe caused by the concentration of CO_2 in the blood ("$PaCO_2$") crossing below an apnic threshold. This abnormally low $PaCO_2$ is likely a result of the preceding hyperpnea **108** that is in turn a manifestation of a ventilatory overshoot.

[0032] Respiratory or ventilatory overshoot describes an excessive response of the physiologic respiratory control system to a sensed change of blood gas composition. In some disordered breathing patients, poor blood flow to the brain causes the central nervous system to perceive CO_2 levels in the blood that are no longer representative of the overall blood CO_2 level. In the case of high sensed CO_2 levels, the central nervous system triggers an increase in respiration in response to the high sensed CO_2 levels, but by the time the chemoreceptors sense the reduced CO_2 level and begin slowing respiration, the CO_2 levels have already become too low. The CO_2 levels may drop below an apnic threshold and as a result respiration may stop or become reduced for a time. CO_2 levels increase during this period of reduced respiration and the cycle of overcorrection of blood gas composition continues or becomes worse. Respiratory overshoot is manifested as excessive minute ventilation or hyperpnea that leads to apnea-hypopnea within the CSR cycle.

[0033] Later in the cycle, the patient's respiratory drive is restored **109** by the increasing blood $PaCO_2$. Chest motion **109** indicates the presence of respiratory drive, but the patient is breathing against the closed airway. No airflow is present. This is obstructive apnea within the same CSR cycle. Later in the cycle the patient's airway opens **110** and chest motion is accompanied by airflow. The natural control system of the respiration in the patient overreacts to the prolonged apnea-hypopnea. Breathing gradually becomes deeper. This is a new cycle of hyperpnea. Excessive escalation of breathing control is the manifestation of another respiratory overshoot.

[0034] FIG. **2** is a representation of a system in accordance with embodiments of the invention as it interacts with a patient's respiratory system. A patient's respiration is monitored **203** by a respiratory sensor that can be, for example, an impedance sensor, a pressure sensor or an accelerometer. A respiratory waveform can be acquired and stored in the system memory. Embedded software analyzes the waveform **204** and detects parameters of a breath such as the breath phase (inspiration or expiration) and tidal volume. At the appropriate time in the breath cycle, such as for example the end of inspiration, a pulse train or signal of stimulation is applied by the stimulation generator **205** to a phrenic nerve. In this embodiment, the pulse train is of sufficient energy to keep one hemidiaphragm muscle contracted (somewhat flattened) thus trapping some amount of air in at least one lung of the patient's respiratory system **202**. This pattern of stimulation results in the inhibition of respiration **206** that may temporarily prevent the natural respiratory pacemaker **201** of the patient from initiating a new breath. It is believed that this may be at least partially accomplished via a vagal feedback into the autonomic control **201** system of the patient from the stretch receptors (mechanoreceptors) of the lung. As a result, the breathing rate of the patient is momentarily reduced. This reduction results in the suppression of respiratory overshoot that would otherwise be caused by the unstable autonomic control. Prevention or reduction of the overshoot may prevent $PaCO_2$ from dropping below the apnic threshold. This may prevent the cessation or clinically undesirable reduction of breathing during the apnea-hypopnea phase of the CSR cycle.

[0035] The described basic operation of the detection and therapy delivery processes of this embodiment can be supplemented by additional control loops to make any stimulation device or other therapy delivery device more practical. For example, software can analyze **207** the respiratory waveform acquired and stored in the device memory for breathing parameters such as respiratory rate, tidal volume, cyclic changes of tidal volume (crescendo-decrescendo), and periodicity of respiration. Based on these parameters the software can determine the settings for the stimulation generator **205**. For example, the duration of the stimulation train **208** can be determined based on the respiratory rate or on the success of the previous cycles of therapy. The stimulation duration can be automatically set to some number between, for example, 0.5 and 60 seconds, thus determining how long the respiratory drive will be suppressed. Based on the available data from the analysis of stored waveforms, the software can also turn therapy on and off **209** or decide to extend one breath or a number of breaths. In one illustrative embodiment stimulation is applied for the duration of a hyperpnea cycle.

[0036] In a further embodiment the software can calculate the respiratory effort breath-to-breath **210** based, for example, on the detected chest motion **203**. Software can adjust stimulation energy **211** by changing, for example, settings for pulse current, signal duration or pulse frequency depending of the detected breath pattern. As used herein, the terms "stimulation signal," "stimulation," "stimulation pulse train," and equivalents refer to a single pulse or a train of pulses that operatively act as a single stimulation event.

[0037] In one embodiment in accordance with the invention, one hemidiaphragm of the patient is stimulated and remains in a relatively contracted state while the other can be naturally relaxed. This results in the trapping of a certain amount of air in the stimulated lung, which may even remain substantially inflated during stimulation. The level of stimulation may be chosen to keep the lung sufficiently inflated so that the stretch receptors in the lung act to activate the afferent vagal feedback to the patient's natural respiration control center in the autonomic nervous system. This feedback may suppress the patient's natural drive to breathe during the stimulation, and for a short time after the stimulation is ended, until both lungs are fully deflated. When the term "stimulated lung" is mentioned, it refers to the lung associated with a stimulated hemidiaphragm or the lung associated with a stimulated phrenic nerve. The term "stimulated lung" is used to simplify the description, and the stimulation of the corresponding hemidiaphragm or phrenic nerve is implied. "Unstimulated lung" can refer to an instance where no stimulation is applied or to a lung that is contralateral to a stimulated lung. It is understood that unless otherwise specified, both the right and left hemidiaphragms and/or phrenic nerves may be stimulated separately and independently, in combination, or in alternating patterns.

[0038] Whether or not the stimulation energy is sufficient to activate this vagal afferent feedback, the stimulated breath is extended. The breathing rate and minute ventilation are momentarily reduced. This results in the reduction of respiratory overshoot and consequentially may prevent blood $PaCO_2$ (Arterial blood carbon dioxide concentration) from dropping below an apnic threshold. As a result, the apnic phase of the CSR cycle may be prevented or substantially reduced in duration and/or severity.

[0039] Software can identify the cyclic breathing or CSR that is a periodic alternation of apnea-hypopnea and hyperpnea phases that together form a CSR cycle. Within the cycle software can identify apnea-hypopnea that is a cessation of breathing for several breaths or several sequential breaths of very week breathing. Software can identify the onset of hyperpnea that is a sequence of breaths with sequentially increasing tidal volume following apnea-hypopnea. Software can extend one or several breaths in the beginning or middle of hyperpnea phase of the cycle.

[0040] Software can analyze the stimulated breaths for the effects of stimulation. These effects can include the additional inhaled volume, duration and presence of a plateau and the increased stimulated breath duration. Software can compare the results of stimulation to the desired settings, to the unstimulated breaths of the same patient and the previous stimulated breaths of the same patient that are stored in the device memory.

[0041] The general purpose of the feedback control is to achieve the desired extension of the breath at the minimum expanding of stimulation energy and with a minimum additional inspired tidal volume that can result from stimulation and additional diaphragmic contraction. Closed loop control algorithms such as PID controllers can be used to meter the adjustments based on the real time information and the process history.

[0042] FIG. **3** is a stylized representation of tidal volume, airflow, and an illustrative stimulation therapy in accordance with embodiments of the invention. Tidal volume waveform **301** and airflow waveform **320** are shown during hyperpnea. Breaths **303**, **304** and **305** sequentially increase in amplitude by increments of tidal volume that exceed 20% of the preceding breath. They therefore meet the criteria for stimulation set by an illustrative software algorithm for the detection of hyperpnea. In addition a tidal volume threshold criterion may set as illustrated by the by the line **308**. In some embodiments, the stimulation pulse train **310** is activated only if the breath tidal volume **309** exceeds the threshold **308**.

[0043] In this embodiment, stimulation is applied at the peak inspiration time point **311** when the breath phases change from inspiration to expiration. In this example three stimulation pulse trains **310**, **312** and **313** are applied to three sequential breaths. In similar embodiments, stimulation may be applied at any point during inspiration. In those embodiments where the stimulation is applied at different points of inspiration, it may be helpful to fashion the stimulation pulse train so that the stimulation is applied somewhat gradually to move the diaphragm to a contracted position more gently to avoid arousing a sleeping patient.

[0044] In some embodiments, an additional stimulation criterion may be set by a blanking period **315**. Blanking period can be set, for example, equal to the duration of time that is between 25% and 90% of the duration of an average spontaneous (unstimulated) breath for the treated patient or to some fixed value such as, for example, one second. The blanking period is applied to avoid double triggering. During the blanking period **315**, stimulation is not allowed even if all other criteria are met. The blanking period can be implemented as a software time counter that starts counting after a stimulation pulse train is applied. In embodiments where the stimulation is not coordinated with the peak of inspiration, the blanking period may be shorter, particularly if the stimulation is configured to hold the lung "still" for a relatively long time.

[0045] FIG. **4** is a stylized representation of a stimulation protocol in accordance with embodiments of the invention. In this embodiment, an adjustment is made based on the results of the stimulation of the previous breath, but it is understood that such an adjustment can be performed based on the acquired respiratory data collected over several stimulated breaths or within the same breath.

[0046] FIG. **4** shows a representation of a respiratory waveform during a hyperpnea cycle. Breath **402** is not stimulated. Breath **403** is the first stimulated breath of the cycle. Stimulation pulse train **404** is applied shortly after the natural inspiration phase **405** of the breath **403** has reached the natural peak inspiration point **408**. In this case the stimulation energy of the pulse train **404** may be excessive. Natural inspiration **405** is followed by the additional inspiration **407** caused by the stimulation and that results in the added tidal volume **409**. Simultaneously with the stimulated lung inspiring the additional volume **409**, the contralateral unstimulated lung starts expiring air **410**. This is the first of two expirations that have been seen during the unilateral (single lung) stimulation performed according to embodiments of the invention. In this example, first lung expiration **410** stops when approximately 50% of air inhaled by the patient during the inspiration phase **405** is exhaled and the patient's lungs enter into a plateau or still period **411**. This still period **411** can be shortened or prolonged by decreasing or increasing the duration of the stimulation pulse train **404**. When stimulation **404** stops, the second (stimulated) lung enters the second expiration phase of the stimulated breath cycle **412** that ends at the point when both lungs are substantially deflated **413**. It is believed that the stimulated lung's stretch receptor feedback inhibits the next breath, which can be started by the autonomic control system after expiration is completed.

[0047] Breath **401** is stimulated by the pulse train **405**. The stimulation energy of the pulse train **405** is reduced compared to the pulse train **404** based on the analysis of the breath **403**. Reduction can be achieved by reducing the electric current of pulse train, the duration of pulse train or the frequency of stimulation. The reduction of energy has the effect on the shape of the breath **401** compared to the breath **403**. Stimulation **405** starts at the peak of natural inspiration **414** and there is no significant additional inspiration or added tidal volume caused by the stimulation. Expiration of the unstimulated lung **415** is followed by a plateau **416** that is followed by the expiration of the stimulated lung **417**. It is understood that the optimization of the stimulation energy can be performed in small increments from one stimulated breath to another and involve feedback mechanisms such as a digital PI or PID regulators and other tools commonly used by engineers to design feedback loops and controls.

[0048] In some embodiments, the stimulation energy is allowed or designed to add tidal volume to an intrinsic breath. This is of course true where the breath is a diminished or apnea-hypopnea breath, but it also may be the case that some therapies are designed or allowed to add tidal volume to intrinsic breaths during normal respiration or hyperpnea (particularly near the start or end of the hyperpnea phase). In these cases calibration of the stimulation signal may be based on factors other than a desire to minimize additional inspiration caused by stimulation.

[0049] FIG. **5** is a stylized representation of tidal volume during a CSR cycle with mixed apnea and several treatment protocols in accordance with embodiments of the invention. The CSR cycle is the same as is shown and described with respect to FIG. **1**. The various treatment protocols, or modes, are shown in a simplified fashion below the representation of the CSR cycle. The effects of the stimulation profile on the tidal volume are not shown in this Figure, but will be discussed here and elsewhere. Mode 1 is a stimulation that begins **500** upon the detection of hyperpnea and continues through the majority of the hyperpnea cycle. It is believed that holding at least one lung still during the hyperpnea cycle reduces respiration during that cycle and thus reduces the likelihood of ventilatory overshoot and a subsequent reduced breathing period that could result from such an overshoot.

[0050] Mode 2 is a stimulate and hold mode similar to mode 1. In mode 2, apnea-hypopnea is detected at **502**. After a delay of an adjustable set amount **504**, a stimulation pulse train is initiated **506** and held through the majority of the hyperpnea cycle. As with any of the modes, the stimulation may be shaped to gradually capture and contract the diaphragm so as to be less likely to arouse the patient or cause discomfort.

[0051] Mode 3 stimulates and holds at least one hemidiaphragm based on a historical average duration of hyperpnea and apnea-hypopnea cycles. If a patient has not immediately responded to therapy, mode 3 would stimulate and hold based on historical durations of apnea-hypopnea **510** and hyperpnea **512**. The stimulation **512** and blanking period **510** would be based on these average durations and not on any real-time detection of breathing parameters. This mode might be useful if a patient's movement during sleep makes it difficult to measure respiration parameters accurately, for example.

[0052] Mode 4 stimulates and holds at least one hemidiaphragm for random periods **514** at random intervals **516**. This mode may be effective because holding at least one lung still during apnea-hypopnea has little effect, while desirable effects flow from holding one lung still during periods of hypopnea. This mode may be effective for some patients and is very simple to implement and manage. This mode may be automatically triggered upon detection of sleep by the use of an accelerometer and/or position sensor or any other means known in the art. Sleep detection may be used to trigger or terminate or otherwise manage any of these modes.

[0053] FIG. **6** is a stylized representation of tidal volume during a CSR cycle with mixed apnea and several treatment protocols in accordance with embodiments of the invention. The CSR cycle is the same as is shown and described with respect to FIG. **1**. The various treatment protocols, or modes, are shown in a simplified fashion below the representation of the CSR cycle. The effects of the stimulation profile on the tidal volume are not shown in this Figure, but will be discussed here and elsewhere. Mode 5 comprises a series of short stimulation signals **602** during apnea-hypopnea. This mode could be employed by detecting actual apnea-hypopnea episodes and stimulating for the majority of the duration of the reduced autonomic breathing. The short pulses of mode 5 are designed to stimulate respiration during the apnea-hypopnea phase where less than normal respiratory drive is present. Each signal is intended to create or augment a breath.

[0054] When employing mode 5, it may be important not to contribute to the hyperventilation or excessive ventilation. Mode 5 will therefore often be configured to stimulate breathing at below mean ventilation levels. One possible way of accomplishing this would be to stimulate one lung at a time. The stimulation could also be set to send the stimulation signals at 50% of normal breathing rate, 50% of the apnea hyperpnea periodic breathing cycle, or some arbitrary low number such as 6-10 breaths per minute or it could be set to stimulate for 50% of the apnea-hypopnea duration, for example. The stimulation of mode 5 during apnea-hypopnea may reduce oxygen desaturation which may reduce respiratory overshoot by keeping the blood gases at a more consistent level.

[0055] Patients with mixed apnea may also differ in the degree of airway obstruction (obstructive component of apnea). In general, the airway diameter may fluctuate with the CSR cycle. The airway may be more open during hyperpnea and gradually more closed during a decrescendo of hyperpnea and apnea-hypopnea. In many cases, significant airway closure is observed towards the end of apnea-hypopnea. This can contribute to arousals at the beginning of hyperpnea, when the patient starts breathing against the closed or significantly obstructed airway. In this regard it may be advisable in some cases to engage the stimulation of mode 5 in the early stages of apnea-hypopnea when airway closure may be less likely.

[0056] Mode 6 comprises a series of short stimulation bursts **604** throughout the CSR cycle. It has been observed that in some patients stimulating throughout CSR without regard to synchronizing the stimulations to breathing or any phase of breathing may "train" the poorly functioning autonomic control to engage in more regular control of breathing. The stimulation signal in mode 6 may be on the order of one to two seconds.

[0057] It has been observed that the crescendo-decrescendo pattern of a typical hyperpnea cycle may represent a relatively strong respiratory drive early in the hyperpnea cycle that gradually decreases during the decrescendo phase of the hyperpnea. It is believed that initiating a mode 6 stimulation pattern after the midpoint of the hyperpnea cycle may be effective in maintaining a regular breathing pattern for the duration of the stimulation and may actually result in regular autonomic breathing once the stimulation is terminated.

[0058] Mode 7 comprises a series of short stimulation bursts **602** during apnea-hypopnea with an extended stimulation and hold during hyperpnea **606**. It has been observed that the drive to hyperventilate in CSR patients may vary throughout the night. For example, it may be most severe early in the sleep cycle and may wane some as the patient falls more deeply into sleep or as therapies mitigate the drive. It may be advisable in some cases to implement mode 7 early in a sleep period and them move to mode 1 or another mode as the therapy mitigates the disordered breathing.

[0059] The reverse may also be true, as the ultimate goal is to stabilize breathing. A patient therapy may be started on mode 1 with the hope that attenuating respiration during hyperpnea will reduce respiratory overshoot and result in autonomic breathing replacing apnea-hypopnea. If mode 1 is not effective in breaking the CSR cycle after some time, the device could switch to mode 7 or some other mode to provide some ventilation during apnea-hypopnea cycles and reduce blood oxygen desaturation incidents.

[0060] Mode 8 comprises a number of longer segmented signals **608** during hyperpnea. The signals are separated by intervals **610** so that the signals hold at least one hemidiaphragm still during hyperpnea for several discontinuous periods.

[0061] All of the modes just described, and others that will occur to those of skill in the art upon reading this disclosure, may be combined into a single therapy delivery device. These modes may be selected based on a patient's response to therapy and other factors considered by practitioners that treat disordered breathing.

[0062] FIG. **7** is a flowchart of a detection and treatment protocol in accordance with embodiments of the invention. Respiratory data of a patient is gathered **700** from sensors capable of detecting signals representative of respiration frequency and amplitude. The data is then analyzed **701** to determine if the patient is experiencing an episode that can be characterized as apnea-hypopnea. Clinically, apnea is defined as 10 seconds or more of very little (less than 10% of normal for the patient) breathing or no breathing at all.

For practical purposes apnea-hypopnea can be detected as 4-9 seconds without breathing or with very shallow breathing. Very shallow breathing can be defined as, for example, less than 5-20% of highest tidal volume previously detected during the previous CSR cycle or over selected several minutes of spontaneous ventilation or as less than 10% of patient's normal, non-periodic breathing. The thresholds for apnea-hypopnea detection can be automatically periodically adjusted based on the respiratory information stored in the device memory or adjusted by a practitioner based on characteristics of the individual patient.

[0063] If apnea-hypopnea is detected, it can be used to enable therapy during a following hyperpnea cycle. The stimulation device may be "armed" **702** upon detection of apnea-hypopnea and would be set to intervene and moderate respiratory overshoot upon the onset of hyperpnea. Intervention can occur within the same CSR cycle or during one of the following cycles.

[0064] In one embodiment the protocol will detect apnea-hypopnea, wait for the first breath that meets the hyperpnea criteria **703**, and start stimulation as soon as the first breath occurs following apnea-hypopnea. In this embodiment, the hyperpnea criteria may be a simple amplitude threshold that is normally crossed as the patient moves from apnea-hypopnea to hyperpnea.

[0065] Another embodiment assumes a relatively long stimulation duration of 30-60 seconds. In this embodiment hyperpnea is suppressed, as in others, and stimulation may or may not be synchronized to inspiration-expiration.

[0066] In another embodiment, the device detects hyperpnea **703** by analyzing the respiratory waveform over several breaths. Hyperpnea can be detected **703**, for example, by three sequential breaths where the tidal volume of the next breath exceeds the tidal volume of the previous breath by 20% or more. If such sequentially escalating breaths are detected, a device may apply stimulation to the following breath or several breaths **704** if armed **705**. It can be expected that the device will intervene and extend at least one breath after, for example, the first 4-10 breathes of hyperpnea are detected and analyzed. Other methods of detecting or declaring hyperpnea may be used without departing from the spirit of this disclosure. Some patients may have hyperpneas that do not follow the crescendo-decrescendo pattern that is frequently found in CSR, and hyperpnea detection criteria can be set on a case-by-case basis.

[0067] The protocol may decide **707** to adjust the parameters of stimulation **706** based on the data collected **700** from the intervention (the physiologic response to stimulation) during one or more previous CSR cycles. These parameters can include: stimulation duration, stimulation energy and the number of extended breaths.

[0068] FIG. **8** is a flowchart of a detection and treatment protocol in accordance with embodiments of the invention. This protocol can be executed alone or in combination with other protocols. For example, this protocol could be executed within the block **704** in FIG. **7**. It could represent the decisions made within one breath after the hyperpnea is identified in block **703** of FIG. **7**. In the event that this protocol is nested within the protocol of FIG. **7**, the redundant steps (i.e., hyperpnea detection) would not be performed.

[0069] In the embodiment of FIG. **8** as a stand-alone protocol, respiratory waveform data is acquired **801** from a respiration sensor in real time, for example every 10 milliseconds. The detected beginning of the inspiration phase of the breath starts the breath analysis **802**. As the data points are acquired, a value representative of inspired tidal volume gradually increases. If hyperpnea is not detected **803**, further respiratory waveform data is gathered **801**. If hyperpnea is detected, parameters such as tidal volume at the end of inspiration, inspiration duration and the rate of inspiration (volume divided by time) are calculated and analyzed **804**.

[0070] The protocol may decide **805** to trigger or not trigger the application of a stimulation pulse train or even to abort the pulse train before the normal duration time based on this constantly updated data stream and analysis. The breath analysis **804** may include, without limitations, the following tests:

[0071] If the inspiration duration is less than a preset time of, for example, 0.5 sec. or is less than 75% of the inspiration time of an average breath for this patient, or some predetermined fraction of the inspiration time of the previous breath, stimulation may not be triggered. Conversely if the inspiration duration is significantly longer than expected, stimulation also may not be triggered.

[0072] FIG. **9** is a flowchart of a stimulation adjustment protocol in accordance with embodiments of the invention. The protocol of FIG. **9** may be used to accomplish the signal adjustment described in relation to FIG. **4**. After the stimulated breath **901** is substantially completed, the additional tidal volume as compared to an unstimulated breath is calculated **902**. If an overstimulation is detected **903**, such as for example an additional 10% of tidal volume is inhaled by the patient after the natural peak of inspiration is reached, the energy of stimulation is adjusted **904** before the stimulation of the next stimulated breath **905**. The adjustment may constitute a 10% reduction of the stimulation current or signal duration.

[0073] FIG. **10** is a flowchart of a stimulation adjustment protocol in accordance with embodiments of the invention. It is possible that, the adjustment of energy illustrated by FIG. **9** can result in the loss of respiratory inhibition or, in the case of nerve stimulation, the loss of nerve capture. This loss of inhibition can be detected by the absence of the stimulated breath plateau (See FIG. **4** and related discussion) in response to the application of stimulation **1001** or by the increase of respiratory rate indicated by the absence of the expected delay **1002** before the next breath **1003**. If the breath is not delayed or the plateau is not detected, the stimulation energy can be increased **1004** to be applied to the next stimulated breath **1005**.

[0074] The general purpose of the feedback control is to achieve the desired contraction of the diaphragm with the minimum expanding of stimulation energy and with a minimum additional inspired tidal volume that can result from stimulation and additional diaphragmic contraction. Closed loop control systems such as PID controllers can be used to meter the adjustments based on the real time information and the process history.

[0075] An alternative method of determining if stimulation capturing the diaphragm is to apply a short stimulation signal during apnea-hypopnea. A short stimulation envelope, for example 2 seconds long, can be applied when no significant natural breathing occurs. The response to this stimulation can be measured as tidal volume or lung volume change. Such a capture test could be performed periodically and the energy of stimulation can be adjusted if indicated.

Such test signals during apnea-hypopnea allow detection of stimulation capture with less interference from natural breathing.

[0076] FIG. **11** is a flowchart of a breath detection protocol in accordance with embodiments of the invention. A signal (N) is captured **1100** from a respiration sensor configured to sense respiratory effort of a patient. The sensor could be an impedance sensor, an accelerometer, an external respiration belt, or any other sensor known in the art. When the protocol is in the inspiration mode **1102**, it counts the signal based on a sample frequency **1104**. The protocol begins with a "MAX" value set at the system minimum and a "MIN" value set to the system maximum. The protocol originally assumes the patient is in inspiration and compares the measured signal to the recorded MAX. If the signal is greater than MAX **1106**, MAX is reset to the signal value **1108**. This continues until the signal is less than MAX, at which time a noise detection protocol **1110** checks that the signal has not dropped an unreasonable amount, which might indicate a signal interruption or noise, and that the count since the beginning of inspiration is greater than a preset or calculated minimum breath duration. If the detected peak of inspiration indicated by the decreasing signal is determined to be real, an amplitude representative of tidal volume is calculated **1112** by subtracting the new MAX from the most recently determined VALLEY (discussed below). If this amplitude passes a noise threshold **1114** the expiration loop is initiated **1116** and a PEAK value is assigned the value of MAX, or the most recent signal.

[0077] The expiration loop **1118** begins with a counter **1120** that accumulates signal data during the expiration cycle. If the signal is less than MIN **1126**, MIN is reset to the signal value **1124**. This continues until the signal is greater than MIN, at which time a noise detection protocol **1128** checks that the signal is not unreasonably greater than MIN and that the count since the beginning of expiration is greater than a preset or calculated minimum breath duration. If the detected valley of expiration indicated by the now-increasing signal is determined to be real, an amplitude representative of tidal volume is calculated **1130** by subtracting the new MIN from the most recently determined PEAK. If this amplitude passes a noise threshold **1132**, the inspiration loop is initiated **1134** and a VALLEY value is assigned to the value of MIN, or the most recent signal.

[0078] From this protocol, or others using the same basic framework or that will occur to those of skill in the art upon reading this disclosure, values for breath frequency or periodicity, amplitude or tidal volume, inspiration duration, expiration duration, cyclic changes of tidal volume, onset an peak of inspiration, onset and peak of expiration and others may be determined. Averages over time or over relevant periods of time may also be calculated. For example, a baseline breath duration may be calculated by measuring breath periodicity over a period of time and calculating an average value. Such baseline development may happen while a patient is awake or at other times when disordered breathing is less likely. Even during periods of CSR, average breath duration can be taken over several cycles of breathing and should remain reasonably constant and provide a good baseline.

[0079] FIG. **12** is a flowchart of a breath detection protocol in accordance with embodiments of the invention. This protocol is another alternative method of determining cycles of inspiration and expiration and associated breathing data. A signal (N) is captured **1200** from a respiration sensor configured to sense respiratory effort of a patient. If the signal is processed through the inspiration loop **1202**, the slope of the signal and the previous signal is determined and compared to zero **1204** to look for an inflection point. If the slope of the signals was positive and is now negative, and a noise threshold test is passed, it can be determined that a peak of inspiration has occurred. The peak value is recorded **1206** and the expiration module **1208** commences. The expiration module **1210** compares the slope of the data points, generally negative throughout expiration depending on the respiration sensor used, until the slope becomes positive. Once the slope of the signals changes from negative to positive, and a noise threshold test is passed, it can be determined that a valley of expiration has occurred and the valley can be recorded **1212** and the inspiration module can begin. This protocol can determine respiration qualities such as breath frequency or periodicity, amplitude or tidal volume, inspiration duration, expiration duration, cyclic changes of tidal volume, onset an peak of inspiration, onset and peak of expiration, for example.

[0080] FIG. **13** is a flowchart of an apnea-hypopnea detection protocol in accordance with embodiments of the invention. The protocol begins when a respiration peak is detected **1300** in accordance with a protocol such as those shown in FIGS. **11** and **12**, or others. The respiration rate is then calculated **1302** based on accumulated data either in the peak detection module or this module. A baseline breath amplitude is determined **1306** for the patient. Such a baseline may be set based on breathing data collected during the day, in the case of a sleep apnea patient, or at any other time that regular breathing may be tracked. Alternatively, a baseline breath amplitude may be determined by a practitioner and preset into the protocol. However determined, the protocol checks to see whether all breaths in the last ten seconds lower than 30% of the baseline **1306**. If so, apnea-hypopnea is detected. Other criteria could be used to detect and declare and episode of apnea-hypopnea, and all are contemplated within the scope of this disclosure.

[0081] FIG. **14** is a flowchart of a hyperpnea detection protocol in accordance with embodiments of the invention. The protocol begins when a respiration peak is detected **1400** in accordance with a protocol such as those shown in FIGS. **11** and **12** or others. The protocol of FIG. **14** determines if the peak is higher than 30% of a baseline breath amplitude **1402** determined as described with respect to FIG. **13**. If there is no such peak, the module waits for the next peak from the peak detection module **1400**. Once the module detects a breath peak higher than 30% of the baseline **1402** it checks for a preceding apnea by determining if all peaks during the last 10 seconds were lower than 30% of baseline **1404**. If both conditions **1402** and **1404** are met, the start of a hyperpnea cycle is detected **1408**. The criteria for steps **1402** and **1404** may be modified as desired without departing from the spirit of this disclosure.

[0082] FIG. **15** is a flowchart of a hyperpnea detection protocol in accordance with embodiments of the invention. The protocol begins when a respiration peak is detected **1500** in accordance with a protocol such as those shown in FIGS. **11** and **12** or others. The protocol of FIG. **15** determines the slope of the last three detected peaks and compares the slope to a predetermined or historically determined threshold **1502**. If the slope of the three peaks exceeds the threshold, the protocol determines whether all peaks recorded during the ten seconds prior to these three peaks had an amplitude lower than 30% of a baseline breath amplitude **1504**. If both conditions **1502** and **1504** are met, the start of a hyperpnea cycle **1508** is detected. The criteria for steps **1402** and **1404** may be modified as desired without departing from the spirit of this disclosure.

[0083] FIG. **16** is a representation of a stimulation signal in accordance with embodiments of the invention. The stimulation signal lasts a stimulation duration or signal duration **1602**. The stimulation signal is made up of a series of pulses **1604** represented by vertical lines in FIG. **16**. In this example, when the stimulation is initiated, the current begins at a base or first level **1606**. In some embodiments, the base current level **1606** is 1-2 milliamps (mA). The stimulation current amplitude then transitions **1610** over a percentage of the total duration to a plateau or second level **1608**. In some embodiments, the plateau current level **1608** may be between 2-4 mA and the time to go from the base current level **1606** to the plateau is about 30% **1610** of the total signal duration **1602**. The current amplitude may transition **1610** from the base current level to the plateau current level in a linear, exponential, or elliptical fashion or any other transition shape that may be useful. The gradual nature of this transition **1610** may help reduce patient discomfort and reduce or eliminate arousals during sleep. The current amplitude may also transition downward **1612** near the end of the stimulation signal in a similar fashion as the initial transition **1610**. This may release the stimulation more gradually and may provide similar benefits for a patient.

[0084] The stimulation pulses **1604** in this example may be delivered at a frequency of 20 Hz and last for a period of 150 μsec. The stimulation duration or signal duration **1602** includes the entire time from that pulses are delivered including transition pulses **1610**, **1612**.

[0085] FIG. **17** shows experimental results of treatment of disordered breathing carried out in accordance with embodiments of the invention. The patient is experiencing CSR as shown by periods of hyperpnea **1702** and apnea-hypopnea **1708**. The hyperpnea exhibits what is commonly referred to as a crescendo **1704**-decrescendo **1706** pattern. The patient's breathing rate during the disordered breathing episodes is approximately 18 breaths per minute. Stimulation signals **1712** are initiated during hyperpnea after the midpoint **1710** of the hyperpnea cycle. The stimulation signals extend the breath duration and slow the breathing rate from 18 breaths per minute to 11 breaths per minute. The stimulation signals are applied to additional future breaths **1714** occurring after the normal duration of the hyperpnea cycle. As can be observed, the CSR cycle is broken and the deleterious effects of CSR including, but not limited to, pulse rate variations, blood gas variations, oxygen desaturation are reduced or eliminated. It is believed that long term health benefits will also accrue, particularly for heart failure patients.

[0086] The extension of breath duration may not result in a lowered breathing rate as measured by breaths per minute. In cases where, for example, a patient is in hyperpnea for 40 seconds and apnea-hypopnea for 20 seconds, a measured breathing rate of 20 breaths per minute might result from a rate of one breath per two seconds (two-second breaths) during the 40-second hyperpnea with little or no breathing activity during the apnea-hypopnea. Extending the breath duration and eliminating or reducing the apnea-hypopnea may, for example, result in a breathing rate of one breath per three seconds (three-second breaths) over an entire minute, which would still result in a measured breathing rate of 20 breaths per minute.

[0087] FIG. **18** shows experimental results of treatment of disordered breathing carried out in accordance with embodiments of the invention. The patient is experiencing CSR as shown by periods of hyperpnea **1802** and apnea-hypopnea **1808**. A stimulation signal **1812** is delivered to one hemidiaphragm at the start of a hyperpnea cycle and the stimulated lung is held open starting at time **1804**. The stimulation signal duration is greater than 50% of a normal hyperpnea duration and the stimulated lung is stilled for that entire time. Muted respiration signals **1806** can be seen throughout the stimulation, likely from the contralateral lung still responding to autonomic signals. The stimulation is repeated **1812** at the start of the next hyperpnea until the CSR cycle is broken.

[0088] While exemplary embodiments of this invention have been illustrated and described, it should be understood that various changes, adaptations, and modifications may be made therein without departing from the spirit of the invention and the scope of the appended claims.

1. A system for treating disordered breathing comprising:

a. a stimulation lead having a stimulation electrode;

b. a respiration sensor; and

c. an energy source, a pulse generator, and circuitry, the circuitry operative to:

i. monitor signals from the respiration sensor and detect apnea-hypopnea; and

ii. deliver a stimulation pulse to the stimulation electrode after the detection of apnea-hypopnea, the stimulation signal having a duration of at least ten seconds.

2. The system of claim **1**, wherein the stimulation signal is delivered after detection of hyperpnea following apnea-hypopnea.

3. The system of claim **1**, wherein the circuitry is operative to:

a. accumulate data from the respiration sensor to determine a value representative of average tidal volume; and

b. detect apnea-hypopnea when the measured value representative of tidal volume is below 30% of the average value for ten seconds.

4. The system of claim **2**, wherein the circuitry is operative to:

a. accumulate data from the respiration sensor to determine a value representative of average tidal volume;

b. detect apnea-hypopnea when the measured value representative of tidal volume is below 30% of the average value for ten seconds; and

c. detect hyperpnea when the value representative of tidal volume exceeds 30% of the average value after apnea-hypopnea has been detected.

5. The system of claim **1**, wherein the signal has a duration of at least twenty seconds.

6. The system of claim **1**, wherein the signal has a duration of at least thirty seconds.

7. The system of claim **3**, wherein the signal has a duration of at least thirty seconds.

8. The system of claim **1**, wherein the stimulation lead is configured to be implanted in a blood vessel proximate a phrenic nerve in a patient.

9. A system for treating disordered breathing comprising:

a. a stimulation lead having a stimulation electrode;

b. a respiration sensor;

c. an energy source, a pulse generator, and circuitry, the circuitry operative to:

i. determine the onset of a hyperpnea based on the respiration sensor signals; and

ii. deliver a stimulation signal to the stimulation electrode during hyperpnea, the signal having a duration of at least one second to extend the duration of a breath.

10. The system of claim **9**, receive signals from the respiration sensor and to calculate a baseline breath duration.

11. The system of claim **10**, wherein the signal duration is at least 25% of the baseline breath duration.

12. The system of claim **9**, wherein the circuitry is operative to determine the peak of inspiration and the signal is initiated proximate the peak of inspiration.

13. The system of claim **9**, wherein the circuitry is operative to determine the onset of inspiration and the signal is initiated proximate the onset of inspiration.

14. The system of claim **9**, wherein the stimulation signal is configured to expand a lung in a patient to a fully inflated position.

15. The system of claim **10**, wherein the signal has a duration of at least 50% of the baseline breath duration.

16. The system of claim **10**, wherein the signal has a duration of at least 75% of the baseline breath duration.

17. The system of claim **10**, wherein the signal has a duration of at least 100% of the baseline breath duration.

18. The system of claim **9**, wherein the respiration sensor is selected from a group consisting of an impedance sensor, a pressure sensor, and an accelerometer.

19. The system of claim **9**, wherein the circuitry is operative to store data relating to respiratory rate, tidal volume, cyclic changes of tidal volume, and periodicity of respiration.

20. The system of claim **9**, wherein circuitry is operative to determine the duration of a hyperpnea cycle and the signal has a duration of greater than 25% of the duration of the hyperpnea cycle.

21-59. (canceled)

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[标]发明人	GELFAND MARK LEVIN HOWARD HALPERT ANDREW PANTELEON ANTONIS		
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摘要(译)

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