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(54) **VAGUS NERVE STIMULATION**

STIMULATION DES VAGUSNERVS

STIMULATION DU NERF VAGUE

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Description

BACKGROUND OF THE INVENTION

Field of the invention

[0001] The present invention is directed generally to neurostimulation of the vagus nerve, and more particularly to an improved apparatus and method for vagus nerve stimulation therapy using heart rate variability synchronization, patterned electrical pulses inside a pulse burst, and electroencephalogram ("EEG") based optimization.

Description of the Related Art

[0002] Vagus nerve stimulation ("VNS") (for example, VNS Therapy™ by Cyberonics, Inc.) is an FDA-approved method for alleviating treatment-resistant epilepsy and depression.

[0003] Vagus nerve stimulation was initially developed and approved by the FDA for the treatment of refractory partial onset epilepsy. Recently, it has been reported that the use of VNS in human patients with epilepsy is associated with an improvement in mood. As a consequence, VNS has also been approved as a treatment for refractory depression (treatment resistant depression).

[0004] VNS typically involves implanting a nerve stimulating electrode on the left or right vagus nerve in the neck. The electrode is connected to a subcutaneous pacemaker-like control unit that generates an electrical nerve stimulating signal. A Vagus Nerve Stimulator ("VNS stimulator") is an example of an implantable stopwatch-sized, pacemaker-like control unit device configured to electrically stimulate the vagus nerve leading to the brain.

[0005] Conventional VNS is generally applied every 5 minutes in a 7 second to one minute burst (see FIG. 3A for a portion of an exemplary burst) including a pulse train of uniformly spaced apart pulses having a pulse current amplitude of about 0.5 mA to about 2.0 mA). The pulses are delivered at about 20 Hz to about 50 Hz. Each of the pulses may have a width of about 0.5 milliseconds. VNS is currently approved to treat epileptic seizures and depression when drugs have been ineffective.

[0006] Consequently, a need exists for methods of delivering electrical stimulation to the vagus nerve. Further, a need exists for improved electrical signals that increase the efficacy of VNS. US2005267542 discloses a vagus nerve stimulating apparatus for treating heart failure, which has an implantable sensor sensing an electrical parameter of a heart, and a control unit driving multipolar electrode device to stimulate a vagus nerve.

SUMMARY OF THE INVENTION

[0007] The invention, as set out in the appended claims, includes a computer readable medium having computer executable components for detecting the QRS wave portion of the cardiac cycle, generating a microburst, and delivering the microburst to the vagus nerve of a patient in response to the detection of the QRS wave portion of the patient's cardiac cycle.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING(S)

[0008]

Figure 1 illustrates a portion of an ECG trace located above a portion of a trace illustrating an exogenous electrical signal patterned into microbursts that are synchronized with the QRS wave portion of the ECG trace. Each of the microbursts begins after a delay period following the QRS wave portion of the ECG trace.

Figure 2A illustrates a conventional electrical signal generator that may be modified to deliver an exogenous electrical signal constructed according to the present invention.

Figure 2B is a block diagram illustrating various components of the electrical signal generator of Figure 2A.

Figure 3A is a trace illustrating an exemplary conventional VNS exogenous electrical signal having a series of pulses.

Figure 3B is a trace of the potential measured in a monkey's thalamus while a portion of the conventional pulse burst of Figure 3A was applied to the vagus nerve of the monkey.

Figure 3C is a trace illustrating an exemplary embodiment of an exogenous electrical signal constructed according to the present invention.

Figure 3D is a trace illustrating the average potential (after 20 microbursts) measured in the monkey thalamus while a pulse burst having microbursts of four pulses each was applied to the vagus nerve. The inter-microburst interval was about 4 seconds and the interpulse interval was about 3 milliseconds.

Figure 3E provides nine exemplary traces of the potential measured inside a monkey's thalamus while various exogenous electrical signals were applied to the vagus nerve of the monkey. Each of the traces illustrates the average potential (after 20 microbursts) measured in the monkey thalamus while the exogenous electrical signals was applied to the monkey's vagus nerve. Each of the exogenous electrical signals included a series of microbursts having a selected number of pulses each. The pulses of the microbursts of the exogenous electrical signals of the topmost row have an interpulse interval of 3 milliseconds. The pulses of the microbursts of the exogenous electrical signals of the middle row have an interpulse interval of 6 milliseconds. The pulses of the microbursts of the exogenous electrical signals of the bottom row have an interpulse interval of 9 milliseconds.

Figure 3F provides three exemplary traces of the potential measured inside a monkey's thalamus while various exogenous electrical signals were applied to the vagus nerve of the monkey. Each of the traces illustrates the average potential (after 20 microbursts) measured in the monkey thalamus while the exogenous electrical signals was applied to the monkey's vagus nerve. All of the exogenous electrical signals included a series of microbursts having three pulses each. The pulses had an interpulse interval of 9 milliseconds. The exogenous electrical signal used to generate the leftmost trace included microbursts separated by an inter-microburst interval of about 6 seconds. The exogenous electrical signal used to generate the middle trace included microbursts separated by an inter-microburst interval of about 2 seconds. The exogenous electrical signal used to generate the rightmost trace included microbursts separated by an inter-microburst interval of about 0.5 seconds.

Figure 4A provides four exemplary traces of the potential measured inside a monkey's thalamus while various exogenous electrical signals were applied to the vagus nerve of the monkey. For all of the exogenous electrical signals, the inter-microburst interval was about 4 seconds and the interpulse interval was about 3 milliseconds.

A topmost trace illustrates the average potential (after 20 pulses) measured in the monkey thalamus while a pulse burst having a series of uniformly spaced apart pulses was applied to the monkey's vagus nerve. The spacing between the pulses was about 4 seconds.

A second trace from the top depicts the average potential (after 20 microbursts) measured in the monkey thalamus while a pulse burst having microbursts of two pulses each was applied to the vagus nerve.

A third trace from the top depicts the average potential (after 20 microbursts) measured in the monkey thalamus while a pulse burst having microbursts of three pulses each was applied to the vagus nerve.

The bottommost trace depicts the average potential (after 20 microbursts) measured in the monkey thalamus while a pulse burst having microbursts of four pulses each was applied to the vagus nerve.

Figure 4B provides five exemplary traces of the potential measured inside a monkey's thalamus while various exogenous electrical signals including microbursts having two pulses each, the microbursts being separated by an inter-microburst interval of about 4 seconds, were applied to the vagus nerve of the monkey. Each of the traces illustrates the average potential (after 20 microbursts) measured in the monkey thalamus while the exogenous electrical signals was applied to the monkey's vagus nerve.

The interpulse interval between the pulses of the microbursts of the exogenous electrical signal was about 40 milliseconds in the topmost trace.

The interpulse interval between the pulses of the microbursts of the exogenous electrical signal was about 20 milliseconds in the trace second from the top.

The interpulse interval between the pulses of the microbursts of the exogenous electrical signal was about 10 milliseconds in the trace third from the top.

The interpulse interval between the pulses of the microbursts of the exogenous electrical signal was about 6.7 milliseconds in the trace fourth from the top.

The interpulse interval between the pulses of the microbursts of the exogenous electrical signal was about 3 milliseconds in the bottommost trace.

Figure 4C provides five exemplary traces of the potential measured inside a monkey's thalamus while various exogenous electrical signals including microbursts having two pulses each, the pulses of each of the microbursts being separated by an interpulse interval of about 6.7 seconds, were applied to the vagus nerve of the monkey. Each of the traces illustrates the average potential (after 20 microbursts) measured in the monkey thalamus while the exogenous electrical signals was applied to the monkey's vagus nerve.

The inter-microburst interval between the microbursts of the exogenous electrical signal used in the topmost trace corresponded to the microbursts occurring at a microburst frequency of about 10 Hz.

The inter-microburst interval between the microbursts of the exogenous electrical signal used in the trace second from the top corresponded to the microbursts occurring at a microburst frequency of about 3 Hz.

The inter-microburst interval between the microbursts of the exogenous electrical signal used in the trace third from the top corresponded to the microbursts occurring at a microburst frequency of about 1 Hz.

The inter-microburst interval between the microbursts of the exogenous electrical signal used in the trace fourth from the top corresponded to the microbursts occurring at a microburst frequency of about 0.3 Hz.

The inter-microburst interval between the microbursts of the exogenous electrical signal used in the bottommost trace corresponded to the microbursts occurring at a microburst frequency of about 0.25 Hz.

Figure 5 illustrates a system for using a conventional EEG device to optimize an exogenous electrical signal used for VNS stimulation according to the present disclosure.

Figure 6 provides an exemplary EEG illustrating the vagal evoked potential elicited by an exogenous electrical signal constructed according to the present invention.

Figure 7 illustrates an exemplary embodiment of an electrical signal generator programming and/or reprogramming device for use with the electrical signal generator of Figure 2A-2B.

DETAILED DESCRIPTION OF THE INVENTION

[0009] The present invention provides novel techniques, alone or in combination, to improve the efficacy of VNS used in the treatment of a variety of medical conditions, including disorders of the nervous system, such as epilepsy and depression. The following disclosure describes various embodiments of a novel method and its associated apparatus for improving VNS therapies. According to the present disclosure, these novel techniques are particularly useful for treating epilepsy and depression. However, it is envisioned that these same novel techniques may be used to treat a variety of disorders and conditions that include a physiological relationship to the nervous system, such as neuropsychiatric disorders, eating disorders/obesity, traumatic brain injury/coma, addiction disorders, dementia, sleep disorders, pain, migraine, endocrine/pancreatic disorders (including but not limited to diabetes), motility disorders, hypertension, congestive heart failure/cardiac capillary growth, hearing disorders, angina, syncope, vocal cord disorders, thyroid disorders, pulmonary disorders, and reproductive endocrine disorders (including infertility). Thus, based on the aforementioned relationship to the nervous system, these disorders and conditions, including epilepsy and depression, are collectively referred to herein as disorders of the nervous system, even if not conventionally described as such.

[0010] One of the novel techniques includes synchronizing portions of an exogenous electrical signal with the endogenous afferent activity of the vagus nerve, primarily the endogenous afferent activity originating from receptors in the heart and lungs. Stimulating the vagus nerve in synchrony with endogenous vagal rhythms, in particular with cardiac cycle and heart rate variability (HRV), enhances therapeutic efficacy of VNS.

[0011] In the prior art, the exogenous electrical signal applied to the vagus nerve during conventional VNS is often referred to as a pulse burst. The pulse burst typically includes a series of uniformly spaced apart substantially identical pulses, i.e., a simple pulse train. The VNS applied to treat disorders of the nervous system may include multiple pulse bursts separated by an interburst delay.

[0012] An individual pulse burst may be triggered automatically or manually. In many prior art devices, a pulse burst may be triggered by the detection of a medical event such as a seizure, or may be triggered manually by the user or a medical professional. Alternatively, pulse bursts may occur at regular intervals separated by a predetermined interburst delay. Typically, the interburst delay is about five minutes, 30 minutes, or 60 minutes.

[0013] The pulses of the conventional VNS pulse bursts are applied asynchronously, i.e., asynchronous with both the cardiac and lung cycles. As mentioned above, conventional VNS is generally applied every 5 minutes in a 7 second to one minute pulse burst (see FIG. 3A for a portion of an exemplary burst) of uniformly spaced apart pulses having an pulse current amplitude of about 0.5 mA to about 2.0 mA. The pulses are delivered at about 20 Hz to about 50 Hz. Each of the pulses may have a width of about 0.5 milliseconds. While monophasic pulses are generally used, biphasic pulses may also be used. As used herein, the term "pulses" refers to both monophasic and biphasic pulses.

[0014] In the present invention, the pulses within a pulse burst are patterned or otherwise organized to improve and/or optimize stimulation of the vagus nerve and/or structures of the brain in communication therewith. The natural endogenous afferent activity in the left and right vagus nerves predominantly occurs immediately following each cardiac contraction and during each inspiration. Further, the timing of the endogenous afferent activity in the left and right vagus nerves varies with heart rate, breathing rate, and emotional state. However, because the left and right vagus nerves innervate different portions of the heart, the timing of the afferent activity in the left vagus nerve may differ from the timing of the afferent activity in the right vagus nerve. Consequently, the patterning of the pulse burst may be different for the right and left vagus nerves. As is appreciated by those of ordinary skill in the art, the pulse burst is generally applied to the left vagus nerve because VNS stimulators implanted on the right side applying a pulse burst to the right vagus nerve are associated with an increase in patient mortality. As used herein, the term "vagus nerve" may refer to either the left or right vagus nerve.

[0015] According to one aspect of the present invention, a novel exogenous electrical signal is applied to the vagus nerve. The novel exogenous electrical signal is configured to augment the natural endogenous afferent activity in the vagus nerve by timing the pulses within a pulse burst in an improved and more effective manner. In particular embodiments, as will be described in detail below, the pulses within the pulse burst may be organized into sub-bursts or microbursts (each having about 2 to about 20 pulses) that are synchronized with the endogenous afferent activity in the vagus nerve to augment the endogenous afferent activity therein.

[0016] Referring to FIG. 1, a trace 100 of a portion of an exemplary embodiment of the novel exogenous electrical signal is provided. Located above the trace 100 in FIG. 1, an exemplary electrocardiogram (ECG) trace 120 depicting cardiac activity detected by an electrocardiograph (not shown) is provided. The novel exogenous electrical signal includes a pulse burst 130 organized into a series of microbursts 170. Each of the microbursts 170 is synchronized with a portion of the cardiac cycle depicted in the ECG trace 120. In particular, each of the microbursts 170 is synchronized with the QRS wave portion 174 of the ECG trace 120, so that endogenous cardiac-related and respiration-related vagal afferent activity is augmented by the microbursts 170 of the exogenous electrical signal.

[0017] As illustrated in FIG. 1, each of the microbursts 170 may be triggered by an R-wave portion 176 of the QRS wave portion 174. Without being bound by theory, it is believed that synchronizing the application of the microbursts 170 of the exogenous electrical signal to the vagus nerve with the detection of the R-wave portion 176 of the patient's cardiac cycle may increase the efficacy of VNS therapy by entraining the exogenous electrical signal with the endogenous cyclic facilitation of central vagal afferent pathways. Each of the microbursts 170 begins after the elapse of a delay period, which comprises a variable time period that may range, e.g., from about 10 milliseconds to about 1000 milliseconds following detection of the R-wave portion 176. In various embodiments, the delay period may be less than about 10 milliseconds. Further, in some embodiments, the delay period may be about 10 milliseconds to about 500 milliseconds or about 10 milliseconds to about 800 milliseconds. In further embodiments, the delay period is less than 1000 milliseconds. In other embodiments, the delay period may be omitted. Each of the delay periods may comprise a predetermined duration such as about 10 milliseconds, or may comprise a random time duration within a predetermined minimum and maximum time duration, e.g., a random time duration from about 10 milliseconds to about 1000 milliseconds. Further, as will be described below, the duration of the delay period preceding each microburst 170 may be determined empirically.

[0018] For example, the leftmost (first) microburst 170 begins after a delay period "D1," the next (or second) microburst 170 begins after a delay period "D2," and the third microburst 170 begins after a delay period "D3." The delay period "D1" may be shorter than the delay periods "D2" and "D3." Additionally, the delay period "D2" may be shorter than the delay period "D3." In alternate embodiments, the delay periods "D1," "D2," and "D3" may be substantially identical. In further embodiments, the delay period "D1," may be larger than delay period "D2," which may be larger than delay period "D3." Embodiments wherein each of the delay periods "D1," "D2," and "D3" is selected randomly within a specified range of delay values or determined empirically are also within the scope of the present invention. As will be appreciated by those of skill in the art, still further embodiments of the present invention may include a variety of delay period combinations that can be identified and implemented by routine experimentation. Each of these is considered to be within the scope of the present invention. While three delay periods have been described with respect to Fig. 1, it is apparent to those of ordinary skill that a delay period may precede each microburst of a pulse burst and the duration of the delay period may be determined empirically or randomly.

[0019] In various embodiments, the synchronization of the exogenous electrical signal further comprises not providing pulses during selected portions of the cardiac cycle, such as periods in the opposite half of the cardiac and respiratory duty cycles, when the central pathways are inhibited. Again without being bound by theory, it is believed that pulses applied to the vagus nerve during the opposite half of the cardiac and respiratory duty cycles are less effective because endogenous signals in this part of the cardiac and/or respiratory cycles are less significant, in terms of their information content, for modulating those portions of the brain relevant to homeostasis mechanisms implicated in medical conditions such as epilepsy and depression. Thus, at least a portion of the asynchronous exogenous electrical signal delivered by current stimulation algorithms, such as conventional VNS, may be therapeutically irrelevant.

[0020] Because the exogenous electrical signal is typically delivered by an implanted device powered by a battery, the delivery of irrelevant signals may result in unnecessary battery depletion. Further, the pulse burst sometimes causes the patient's vocal cords to contract causing his/her voice to become horse, which is uncomfortable and makes talking difficult. Sometimes, the pulse burst causes neck pain and may cause cardiac problems. Therefore, reducing the number of pulses may contribute to patient comfort and/or safety.

[0021] Synchronizing the microbursts 170 of the exogenous electrical signal with each individual QRS wave portion 174 also tracks the natural variability in vagal afferent activity that occurs during breathing and emotional shifts. This heart rate variability (HRV) is a function of respiration and efferent sympathovagal tone. During inspiration, the heart rate accelerates and during expiration it decelerates. Thus, an R-R interval (i.e., the time that elapses between successive R wave portions 176) appearing in the ECG is shorter during inspiration and longer during expiration, producing HRV. HRV is also known as respiratory sinus arrhythmia. Additionally, it is well established that a larger HRV is associated with greater physical health, including greater immune function, lower risk of cardiac arrhythmia, and better mood, than a smaller HRV.

[0022] HRV is greatly increased during meditation, and HRV is increased easily by slow, paced breathing. Synchronizing the microbursts 170 of the exogenous electrical signal with each QRS wave portion 174 of the cardiac cycle utilizes and accentuates the positive association of HRV with overall bodily health. Further, it helps ensure that the microbursts 170 of the exogenous electrical signal are synchronized with variances in the cardiac cycle. Consequently, it may be beneficial for the patient to begin paced breathing during the pulse burst. Further, it may improve the efficacy of the exogenous electrical signal if the pulse burst is triggered while the patient is performing paced breathing.

[0023] Referring to FIG. 2A-2B, a suitable electrical signal generator 200, such as a VNS stimulator, known in the art has one or more electrodes 220A and 220B coupled to the vagus nerve for delivering electrical pulses thereto. In embodiments wherein the microbursts of the exogenous electrical signal are synchronized with the cardiac cycle, optionally, the electrical signal generator 200 has the capacity to detect cardiac signals and produce an ECG trace for the purpose of avoiding the deliverance of conventional VNS in the event of cardiac arrest. In other words, the suitable electrical signal generator 200 for use with the present invention may include one or more sensors, such as sensing electrodes 210A and 210B positioned to detect cardiac electrical signals, and the onboard capability of analyzing those signals. In particular, the electrical signal generator 200 may be capable of identifying the R wave portion of the cardiac signal. In alternative embodiments, the sensor(s) may include an acoustic device configured to detect the cardiac cycle.

[0024] In embodiments wherein the microbursts of the exogenous electrical signal are synchronized with the cardiac cycle, the electrical signal generator 200 may be modified or programmed to deliver the novel exogenous electrical signal. The modifications include replacing a more common open-loop or non-feedback stimulation system with a feedback system utilizing one or more sensing electrodes 210A and 210B to detect the QRS wave portion 174 of the ECG trace 120 (see FIG. 1). The modification of the electrical signal generator 200 is effected by programming the electrical signal generator 200 to initiate a microburst 170 after the elapse of the delay period, such as delay period "D1", delay period "D2", or delay period "D3," following the detection of the QRS wave portion 174. Again, while three exemplary delay periods have been described, a delay period may precede each microburst and such embodiments are within the scope of the present invention. Further, embodiments in which no delay period precedes a microburst are also within scope of the present invention. As is apparent to those of ordinary skill in the art, embodiments of the electrical signal generator 200 that have the feedback system for detecting the QRS wave portion 174 without modification are also within the scope of the present invention.

[0025] FIG. 2B is a block diagram of various components of the electrical signal generator 200. The electrical signal generator 200 may include a programmable central processing unit (CPU) 230 which may be implemented by any known technology, such as a microprocessor, microcontroller, application-specific integrated circuit (ASIC), digital signal processor (DSP), or the like. The CPU 230 may be integrated into an electrical circuit, such as a conventional circuit board, that supplies power to the CPU 230. The CPU 230 may include internal memory or memory 240 may be coupled thereto. The memory 240 is a computer readable medium that includes instructions or computer executable components that are executed by the CPU 230. The memory 240 may be coupled to the CPU 230 by an internal bus 250.

[0026] The memory 240 may comprise random access memory (RAM) and read-only memory (ROM). The memory 240 contains instructions and data that control the operation of the CPU 230. The memory 240 may also include a basic input/output system (BIOS), which contains the basic routines that help transfer information between elements within the electrical signal generator 200. The present invention is not limited by the specific hardware component(s) used to implement the CPU 230 or memory 240 components of the electrical signal generator 200.

[0027] The electrical signal generator 200 may also include an external device interface 260 permitting the user or a medical professional to enter control commands, such as a command triggering the delivery of the novel exogenous electrical signal, commands providing new instructions to be executed by the CPU 230, commands changing parameters related to the novel exogenous electrical signal delivered by the electrical signal generator 200, and the like, into the electrical signal generator 200. The external device interface 260 may include a wireless user input device. The external device interface 260 may include an antenna (not shown) for receiving a command signal, such as a radio frequency (RF) signal, from a wireless user input device such as a computer-controlled programming wand 800 (see FIG. 7). The electrical signal generator 200 may also include software components for interpreting the command signal and executing control commands included in the command signal. These software components may be stored in the memory 240.

[0028] The electrical signal generator 200 includes a cardiac signal interface 212 coupled to sensing electrodes 210A and 210B for receiving cardiac electrical signals. The cardiac signal interface 212 may include any standard electrical interface known in the art for connecting a signal carrying wire to a conventional circuit board as well as any components capable of communicating a low voltage time varying signal received from the sensing electrodes 210A and 210B through an internal bus 214 to the CPU 230. The cardiac signal interface 212 may include hardware components such as memory as well as standard signal processing components such as an analog to digital converter, amplifiers, filters, and the like.

[0029] The electrical signal generator 200 includes an exogenous electrical signal interface 222 coupled to electrodes 220A and 220B for delivering the exogenous electrical signal to the vagus nerve. The exogenous electrical signal interface 222 may include any standard electrical interface known in the art for connecting a signal carrying wire to a conventional circuit board as well as any components capable of communicating a low voltage time varying signal generated by the CPU 230 or a signal generating device controlled by the CPU 230 to the electrodes 220A and 220B through an internal bus 252. The exogenous electrical signal interface 222 may include hardware components such as memory as well as standard signal processing components such as a digital to analog converter, amplifiers, filters, and the like.

[0030] The various components of the electrical signal generator 200 may be coupled together by the internal buses 214, 250, 252, and 254. Each of the internal buses

214, 250, 252, and 254 may be constructed using a data bus, control bus, power bus, I/O bus, and the like.

[0031] The electrical signal generator 200 may include instructions 280 executable by the CPU 230 for processing and/or analyzing the cardiac electrical signals received by the sensing electrodes 210A and 210B. Additionally, the electrical signal generator 200 may include instructions 280 executable by the CPU 230 for generating an exogenous electrical signal delivered to the vagus nerve by the electrodes 220A and 220B. These instructions may include computer readable software components or modules stored in the memory 240. The instructions 280 may include a Cardiac Signal Monitoring Module 282 that generates a traditional ECG trace from the cardiac electrical signals. The Cardiac Signal Monitoring Module 282 may record the ECG trace in the memory 240.

[0032] As is appreciated by those of ordinary skill in the art, generating an ECG trace from an analog cardiac electrical signal may require digital or analog hardware components, such as an analog to digital converter, amplifiers, filters, and the like and such embodiments are within the scope of the present invention. In one embodiment, some or all of these components may be included in the cardiac signal interface 212. In an alternate embodiment, some or all of these components may be implemented by software instructions included in the Cardiac Signal Monitoring Module 282. The Cardiac Signal Monitoring Module 282 may include any method known in the art for generating an ECG trace from a time varying voltage signal.

[0033] As mentioned above, the unmodified electrical signal generator 200 monitors cardiac electrical signals for the purposes of detecting a cardiac arrest. The Cardiac Signal Monitoring Module 282 may be modified to include instructions for detecting or identifying the R wave portion of the ECG trace. The R wave portion of the ECG trace may be detected using any method known in the art. While the electrical signal generator 200 has been described as having the Cardiac Signal Monitoring Module 282, embodiments in which the functionality of the Cardiac Signal Monitoring Module 282 is performed by more than one software component are within the scope of the present invention.

[0034] The unmodified electrical signal generator 200 generates the exogenous electrical signal used by conventional VNS. The instructions 280 include a Signal Generation Module 284 for instructing the CPU 230 how and when to generate the conventional VNS exogenous electrical signal and deliver it to the vagus nerve via the electrodes 220A and 220B. The Signal Generation Module 284 may be modified to generate the inventive novel exogenous electrical signal. Specifically, the Signal Generation Module 284 may be modified to include instructions directing the CPU 230 to synchronize the microbursts of the exogenous electrical signal with the R wave portion of the ECG trace. The Signal Generation Module 284 may determine the values of the various parameters used to define the novel exogenous electrical signal based on simulating the endogenous afferent activity of the vagus nerve as described herein. Alternatively, the values of the various parameters may be stored in the memory 240 and used by the Signal Generation Module 284 to generate the novel exogenous electrical signal. The various parameters may be entered into the memory 240 by the external device interface 260 which permits the user or medical professional to enter control commands, including commands changing parameters related to the novel exogenous electrical signal delivered by the electrical signal generator 200, and the like, into the electrical signal generator 200.

[0035] While the electrical signal generator 200 has been described as having the Signal Generation Module 284, embodiments in which the functionality of the Signal Generation Module 284 is performed by more than one software component are within the scope of the present invention.

[0036] Examples of suitable electrical signal generators for use with the present invention include a model 103 VNS stimulator (formally referred to as the Gen39) produced by Cyberonics, Inc. (Houston, TX), model 104 VNS stimulator also produced by Cyberonics, Inc., and the like. The analog recording and ECG recognition capacity of these VNS stimulators enable their onboard processor to be programmed to produce pulse bursts of vagal stimulation having the desired parameters at variable delay periods following the detection of the R-wave of the ECG. The delay periods may comprise a predetermined, programmable duration such as about 10 milliseconds, or may comprise a random time duration within a predetermined programmable minimum and maximum time duration, e.g., a random time duration from about 10 milliseconds to about 1000 milliseconds. The predetermined, programmable duration(s) of the delay period(s) may be determined empirically using methods described below.

[0037] While a relatively sophisticated embodiment of the electrical signal generator 200 is described above, those of ordinary skill appreciate that simpler devices, such as a device configured to deliver the exogenous electrical signal asynchronously (i.e., an exogenous electrical signal having microbursts that are not synchronized with the cardiac cycle) are also within the scope of the present invention. The electrical signal generator 200 may provide an asynchronous exogenous electrical signal having microbursts spaced at regular or variable intervals. For example, the microbursts may occur at least every 100 milliseconds or at the microburst frequency of about 0.25 Hz to about 10 Hz. The pulses within the microbursts may be spaced at regular or variable intervals. Further, less sophisticated embodiments of the electrical signal generator 200 include electrical signal generators that are pre-programmed with the exogenous electrical signal parameters (e.g., pulse width, pulse frequency, interpulse interval(s), microburst frequency, number of pulses in the microbursts, etc.) before implementation and may retain those pre-programmed parameter values throughout the functional life of the electrical signal generator. Alternatively, electrical signal generators configured to generate an asynchronous exogenous electrical signal may be programmable after implementation. For example, the computer-controlled programming wand 800 (see FIG. 7) may be used in the manner described above to program such electrical signal generators. As is readily apparent to those of ordinary skill, the present invention is not limited by the particular electrical signal generator used to generate the inventive exogenous electrical signal.

[0038] In one aspect, the microbursts of the exogenous electrical signal may be delivered following every detected R-wave occurring within a predetermined pulse burst period, i.e., the period of time during which the exogenous electrical signal is generated. In another embodiment, the microbursts may be applied to the vagus nerve only during the inspiratory phase. This may be implemented by programming the electrical signal generator 200 to apply a microburst only on the shortening R-R intervals during HRV, i.e., only on an R-wave having an R-R interval less than the preceding R-R interval, or less than a moving average for several R-R intervals, e.g., less than a 5 or 10 R-R interval moving average. In further embodiments, the electrical signal generator 200 may include a sensor, such as a strain gauge or acoustic device, that detects various biometric parameters such as heartbeat and the respiratory cycle. For example, a strain gauge may be used to determine inspiration is occurring by identifying when the chest is expanding. The invention is not limited by the method used to determine inspiration is occurring, the R-R interval, and/or whether the R-R intervals are shortening for the purposes of determining inspiration is occurring.

[0039] The timing parameters defining how the microbursts of the exogenous electrical signal are synchronized with the cardiac cycle for maximal therapeutic efficacy may be determined empirically, and according to particular embodiments, are individually optimized for each patient (as described below). In alternate embodiments, patients may perform paced breathing, e.g., taking a breath at a frequency of about 0.1 Hz, during periods when the exogenous electrical signal is being delivered to the vagus nerve, to facilitate or increase the amount of HRV.

[0040] In further embodiments, the various parameters of the cardiac cycle synchronized exogenous electrical signal may be varied, including without limitation the duration of the pulse burst, the delay period(s) following R-wave detection, the number of pulses comprising a microburst, the interpulse interval (i.e., the amount of time separating one pulse from an adjacent pulse), and the inter-microburst interval (i.e., the amount of time between successive microbursts). Further, these parameters may be selectively associated with particular R-waves of the respiratory cycle, depending on the length of each preceding R-R-interval. In various embodiments, these parameters are empirically optimized for each patient.

[0041] In another aspect of the present invention, a method of providing an exogenous electrical signal capable of inducing a much larger vagal evoked potential (VEP) than that induced by conventional VNS is provided. The exogenous electrical signal provided to the vagus nerve comprises a pulse burst including a series of microbursts. As described above the inter-microburst interval may be determined by the cardiac cycle.

[0042] An example of a portion of a pulse burst 300 used in conventional VNS may be viewed in FIG. 3A. The pulse burst 300 includes a plurality of uniformly spaced apart pulses 302 occurring about every 20 milliseconds to about every 50 milliseconds, i.e., occurring at a frequency of about 20 Hz to about 50 Hz. A conventional pulse burst, such as pulse burst 300 may have a pulse burst duration of about 7 seconds to about 60 seconds (resulting in a pulse burst having from about 140 to about 3000 pulses or more). Each pulse 302 may have a width or duration of about 50 microseconds to about 1000 microseconds (μsec) and a pulse current of about 0.1 mA to about 8 mA.

[0043] The pulse burst 300 may be separated from a pulse burst identical to pulse burst 300 by an interburst interval of about 5 min. Sometimes, an interburst interval of about 30 min. or about 60 min. is used. In further implementations, the pulse burst 300 is triggered by the onset of a medical event, such as a seizure, or is triggered by the user or a medical professional. In such embodiments, the interburst interval varies.

[0044] FIG. 3B provides a trace 304 of the potential measured in the monkey thalamus while the conventional pulse burst 300 (see FIG. 3A) of uniformly spaced pulses 302 having an interpulse interval of 4 seconds was applied to the vagus nerve. The trace 304 shows the potential inside the thalamus immediately after each of the pulses 302 is delivered to the vagus nerve. An increased VEP 305 occurs after the first pulse 302. However, as illustrated by FIG. 3B, little to no increased VEP is observed after the successive pulses 302 in the series. The average potential inside the thalamus observed over 20 pulses is provided by a topmost trace 320 in FIG. 4A. The VEP is the difference between a minimum average potential in the trace 320 observed after an averaged pulse portion 303 of the trace 320 and a maximum average potential in the trace 320 observed after the averaged pulse portion 303 of the trace 320. However, as illustrated in the trace 320, the minimum and the maximum potentials are not clearly identifiable.

[0045] Referring to FIG. 3C, a portion of a pulse burst 400 of the exogenous electrical signal constructed in accordance with the present invention is provided. As is apparent to those of ordinary skill, unlike the uniformly spaced pulses 302 of the pulse burst 300, the pulses 402 and 404 of the pulse burst 400 are patterned or structured within the pulse burst 400. Specifically, the pulses 402 and 404 are arranged into microbursts 410A, 410B, and 410C. In the embodiment depicted in FIG. 3C, each of the microbursts 410A, 410B, and 410C includes the pulse 402 followed by the pulse 404. Each of the individual pulses 402 and 404 in the pulse burst 400 resemble the pulses 302 of the conventional VNS pulse burst 300 and have a pulse width of about 50 microseconds to about 1000 microseconds (μsec) and a pulse current of about 0.25 mA to about 8 mA. In particular embodiments, the pulse current is less than about 2 mA.

[0046] While the individual pulses 402 and 404 in the pulse burst 400 resemble the pulses 302 of the conventional VNS pulse burst 300 (i.e., each has a pulse width of about 50 microseconds to about 1000 microseconds (μsec) and a pulse current of about 0.25 mA to about 8 mA) the number of pulses 402 and 404 in the pulse burst 400 is markedly smaller than the number of pulses 302 in the pulse burst 300, assuming the pulse burst 400 has the same duration as the pulse burst 300. As mentioned above, the conventional pulse burst 300 may have a pulse burst duration of about 7 seconds to about 60 seconds and a pulse frequency of about 20 Hz to about 50 Hz, resulting in a pulse burst having from about 140 to about 3000 pulses or more. If the pulse burst 400 has a duration of about 7 seconds to about 60 seconds, and the microbursts are delivered every 0.5 seconds, roughly corresponding to the interval between heart beats during inspiration, the pulse burst 400 will have about 30 pulses to about 242 pulses.

[0047] As mentioned above, reducing the number of pulses delivered to the vagus nerve may help prolong battery life as well as improve patient comfort and safety. Further, patterning the pulses of the pulse burst 400 into microbursts, such as microbursts 410A, 410B, and 410C increases the VEP observed in the brain. Because the VEP is increased, the current amplitude may be reduced, further increasing patient comfort and/or safety. The increased VEP may also improve the therapeutic effects of the exogenous electrical signal.

[0048] Referring to FIG. 3D, a trace 306 illustrating the average potential inside the monkey thalamus observed over a series of 20 microbursts, each having a series of four pulses with a 3 milliseconds interpulse interval separating the pulses, is provided. The microbursts of FIG. 3D are separated by a 4 second inter-microburst interval. The VEP is the difference between a minimum 307 in the trace 306 observed after an averaged microburst portion 309 of the trace 306 and a maximum 308 in the trace 306 observed after the averaged microburst portion 309 of the trace 306. The difference between the minimum 307 and the maximum 308 of the trace 306 is clearly larger than the difference between the unidentifiable minimum and the unidentifiable maximum of the trace 320 (see FIG. 4A and the pulse intervals after the third pulse in FIG. 3B). Therefore, without changing any parameters other than the number of pulses delivered every 4 sec., i.e., delivering a microburst instead of a single pulse, the VEP potential can be increased or enhanced.

[0049] The pulses 402 and 404 within the first microburst 410A are separated by an interpulse interval "P1A." The pulses 402 and 404 within the second microburst 410B are separated by an interpulse interval "P1B." The pulses 402 and 404 within the third microburst 410C are separated by an interpulse interval "P1C." In most cases, the interpulse intervals "P1A," "P1B,"and "P1C" separating the pulses 402 and 404 are shorter than the interpulse intervals between the pulses 302 used in conventional VNS therapy. The first interpulse interval "P1A" may range from about one millisecond to about 50 milliseconds. Typically, the first interpulse interval "P1A" may range from about 2 milliseconds to about 10 milliseconds. In some embodiments, Typically, the first interpulse interval "P1A" may range from about 3 milliseconds to about 10 milliseconds. In various embodiments, the interpulse interval "P1 B" may be substantially equal to the interpulse interval "P1A." Subsequent interpulse intervals occurring after the interpulse interval "P1B," such as interpulse interval "P1C," may be substantially equal to the interpulse interval "P1B." In alternate embodiments, the interpulse interval "P1A" may be larger than the interpulse interval "P1B," which may be larger than the interpulse interval "P1C." In further embodiments, the interpulse interval "P1A" may be smaller than the interpulse interval "P1B," which may be smaller than the interpulse interval "P1C." In various embodiments, the interpulse intervals "P1A," "P1B," and "P1C" may be selected randomly from a predetermined range of interpulse interval values. In further embodiments, the interpulse intervals may be variable and determined empirically, as described below.

[0050] The first microburst 410A is separated from the microburst 410B by an inter-microburst interval "P2." Each microburst may be considered an event occurring at a microburst frequency (i.e., the inverse of the sum of the inter-microburst interval "P2" and the duration of the microburst). The microburst frequency may range from about 0.25 Hz to about 10 Hz. It may be beneficial to use a microburst frequency that approximates the R-R cycle of the patient.

[0051] In various embodiments, the pulses within a microburst may be patterned or structured. For example, referring to FIG. 1, the portion of the pulse burst 130 is provided. The pulse burst 130 includes five microbursts 170, each triggered by the R-wave portion 176 of the cardiac cycle depicted in the ECG trace 120. Each microburst 170 includes four pulses 182, 184, 186, and 188. The first pulse 182 begins after the predetermined delay time "D1" has elapsed following the identification of the R-wave portion 176. The pulse 184 follows the pulse 182 after a first interpulse delay has elapsed. Then, after a second interpulse interval, the pulse 186 is generated. Finally, after a third interpulse interval, the pulse 188 is generated. In the embodiment depicted in FIG. 1, the interpulse intervals increase in duration along the series of pulses. However, the interpulse intervals may be determined empirically and individualized for each patient. While each microburst 170 in FIG. 1 has only four pulses, microbursts 170 having 2 to 20 pulses, and consequently

1 to 19 interpulse intervals, are within the scope of the present invention. In some embodiments, the microbursts 170 may have 2 to 15 pulse, or alternatively, 3 to 6 pulses.

[0052] In various embodiments, the pulse burst 400 may be separated from a pulse burst identical to pulse burst 400 or a dissimilar pulse burst by an interburst interval of about 5 minutes to about 240 minutes. Alternatively, the interburst interval may be about 200 milliseconds to about 24 hours. In further embodiments, the pulse burst is applied continuously. The pulse burst may have a duration of about 100 milliseconds to about 60 minutes. In various embodiments, the pulse burst duration is determined empirically for a particular patient and/or medical condition. In further embodiments, the pulse burst 400 is triggered by the onset of a medical event, such as a seizure, or is triggered by the user or a medical professional. In such embodiments, the interburst interval varies. Optionally, the pulse burst 400 may be terminated automatically by the onset of a medical event, such as cardiac arrest, or manually the user or a medical professional. In such embodiments, the pulse burst duration varies.

[0053] Pulses, such as pulses 182, 184, 186, and 188, arranged into microbursts, such as microburst 170, are capable of evoking an enhanced vagal evoked potential (eVEP) in the patient's brain that is significantly greater than an VEP evoked by conventional VNS (see FIG. 3A). However, this eVEP may attenuate as the number of pulses within a microburst increases beyond an optimal number of pulses. Framed a little differently, the eVEP attenuates as the microburst duration increases beyond an optimal duration. Thus, for example, where a microburst exceeds 2 pulses to 5 pulses, the eVEP begins to diminish, and if more than 20 pulses are provided, the eVEP essentially disappears. This may be observed in FIG. 3E.

[0054] Referring to the top row of FIG. 3E, traces 370, 372, and 374 illustrate the average potential inside the monkey thalamus averaged over a series of 20 microbursts, each having a series of pulses separated by an interpulse interval of 3 milliseconds. The microbursts of FIG. 3E are separated by a 4 second inter-microburst interval. The number of pulses within the microbursts increase from left to right. In the leftmost trace 370, the microbursts had 2 pulses each. In the center trace 372, the microbursts had 5 pulses each. And, in the rightmost trace 374, the microbursts had 9 pulses each. Again, the VEP observed in each trace, is the difference between a minimum in the trace observed after an averaged microburst portion (appearing at the left of the trace) and a maximum in the trace observed after the averaged microburst portion of the trace. The top row clearly illustrates that using these parameters, microbursts having 5 pulses produce a larger VEP than microbursts having 2 pulses. However, microbursts having 9 pulses produce a smaller VEP than microbursts having 5 pulses.

[0055] Referring to the middle row of FIG. 3E, traces 380, 382, and 384 illustrate the average potential inside the monkey thalamus averaged over a series of 20 microbursts, each having a series of pulses separated by an interpulse interval of 6 milliseconds. In the leftmost trace 380, the microbursts had 2 pulses each. In the center trace 382, the microbursts had 3 pulses each. And, in the rightmost trace 384, the microbursts had 6 pulses each. The middle row clearly illustrates that using these parameters, microbursts having 3 pulses produce a larger VEP than microbursts having 2 pulses. However, microbursts having 6 pulses produce a smaller VEP than microbursts having 3 pulses.

[0056] Referring to the bottom row of FIG. 3E, traces 390, 392, and 394 illustrate the average potential inside the monkey thalamus averaged over a series of 20 microbursts, each having a series of pulses separated by an interpulse interval of 9 milliseconds. In the leftmost trace 390, the microbursts had 2 pulses each. In the center trace 392, the microbursts had 3 pulses each. And, in the rightmost trace 394, the microbursts had 5 pulses each. The bottom row clearly illustrates that using these parameters, microbursts having 3 pulses produce a larger VEP than microbursts having 2 pulses. However, microbursts having 5 pulses produce a smaller VEP than microbursts having 3 pulses.

[0057] Referring to the leftmost column of FIG. 3E, traces 370, 380, and 390 illustrate the facilitation the first pulse provides to the second pulse of the microburst. The traces 372, 382, and 392 in the rightmost column of FIG. 3E illustrate additional facilitation provided by adding additional pulses to the microburst. However, the traces 374, 384, and 394 in the rightmost column of FIG. 3E illustrate that if the duration of the microbursts is too long, the microburst extends into an inhibitory period of neural activity reducing the VEP observed in the thalamus of the monkey. Consequently, the VEP may be improved and/or optimized by the selection of the number of pulses of the microbursts.

[0058] It may be helpful to define a microburst by its duration rather than the number of pulses. Experimental results related to optimizing microburst duration are illustrated in FIG. 3E and 4B. For example, ignoring the pulse widths, FIG. 3E illustrates that the VEP begins to decline when the sum of the interpulse intervals within a single microburst exceeds about 30 milliseconds. Consequently, for the monkey, the optimal sum of the interpulse intervals within a single microburst may be less than 30 milliseconds and in some embodiments, less than 20 milliseconds. The data of FIG. 3E further indicates, a range of about 12 milliseconds to about 18 milliseconds may be used. Human beings are larger and have a heart rate that is roughly half (about 180 beats/minute for the monkey and about 70 beats/minute for a human). Therefore, one of ordinary skill will recognize that by doubling the sum of the interpulse intervals, the sum of the interpulse intervals may be converted for use with a human. Based on this rough approximation, for humans, the optimal sum of the interpulse intervals within a single microburst may be less than 80 milliseconds and in some embodiments, the sum may be less than 60 milliseconds. In further embodiments, the sum of the interpulse intervals within a single microburst may be less than about 40 milliseconds and preferably about 12 milliseconds to about 40 milliseconds. In some embodiments, the sum of the interpulse intervals within a single microburst may be about 10 milliseconds to about 80 milliseconds. One of ordinary skill in the art will also recognize alternate methods of converting the sum of the interpulse intervals determined in the experimental monkey data for use with a human and that such embodiments are within the scope of the present invention. Further, the sum of the interpulse intervals for use with a human may be determined empirically using the empirical method described below.

[0059] Generally, the microburst duration (i.e., the sum of the interpulse intervals and the pulse widths within a microburst) may be less than about one second. In particular embodiments, the microburst duration may be less than about 100 milliseconds. In particular embodiments, microbursts having a duration of about 4 milliseconds to about 40 milliseconds may be used.

[0060] Referring to the top row of FIG. 3F, traces 391, 393, and 395 illustrate the average potential inside the monkey thalamus averaged over a series of 20 microbursts, each having a series of pulses separated by an interpulse interval of about 9 milliseconds. The microbursts used to create the traces 391, 393, and 395 are separated by about a 6 second, about a 2 second, and about a 0.5 second inter-microburst interval, respectively. While the VEP in the trace 395 is less than the VEP in the other two traces 393, and 395, the trace 395 illustrates that the eVEP is present at the rate the QRS wave occurs in the cardiac cycle during inspiration, i.e., about once every 0.5 second. Consequently, microbursts synchronized with the QRS wave during inspiration may produce eVEP in the thalamus and other brain structures in electrical communication therewith. Other parameters, such as interpulse interval(s), delay period(s), pulse current amplitude, pulse width, pulse burst duration, and the like may be adjusted to improve and/or optimize the VEP.

[0061] To maintain the eVEP, the present invention provides a microburst having only a small number of pulses as well as an inter-microburst interval that serves as a period during which the vagus nerve (and/or brain structures in communication therewith) may recover from the microburst. Providing an appropriate inter-microburst interval helps ensure that the succeeding microburst in the pulse burst of the exogenous electrical signal is capable of generating the eVEP. In some embodiments, the inter-microburst interval is as long as or longer than the duration of the microburst. In another embodiment, the inter-microburst interval is at least 100 milliseconds. In further embodiments, the inter-microburst interval may be as long as 4 seconds or 6 seconds. In some embodiments, the inter-microburst interval may be as long as 10 seconds. Each microburst comprises a series of pulses that, in some embodiments, are intended to mimic the endogenous afferent activity on the vagus nerve. In one embodiment, the microburst may simulate the endogenous afferent vagal action, such as the action potentials associated with each cardiac and respiratory cycle.

[0062] The central vagal afferent pathways involve two or more synapses before producing activity in the forebrain. Each synaptic transfer is a potential site of facilitation and a nonlinear temporal filter, for which the sequence of inter-microburst intervals and/or interpulse intervals within a microburst can be optimized. Without being bound by theory, it is believed that the use of microbursts enhances VNS efficacy by augmenting synaptic facilitation and "tuning" the input stimulus train to maximize the forebrain evoked potential.

[0063] FIG. 4A-4C illustrate the effects of modifying the various parameters of the exogenous electrical signal on the VEP measured in the thalamus of a monkey. FIG. 4A illustrates the effects of varying the number of pulses in a microburst. FIG. 4B illustrates the effects of varying the interpulse interval between the pulses of a microburst having only two pulses. FIG. 4C illustrates the effects of varying the inter-microburst interval between adjacent microbursts having only two pulses each.

[0064] The topmost trace 320 of FIG. 4A provides the average potential (after 20 pulses) measured in the monkey thalamus while a pulse burst of uniformly spaced apart pulses having an interpulse interval of 4 seconds was applied to the vagus nerve.

[0065] A trace 340 of FIG. 4A depicts the average potential (after 20 microbursts) measured in the monkey thalamus while a pulse burst having microbursts of two pulses each was applied to the vagus nerve. The inter-microburst interval was about 4 seconds and the interpulse interval was about 3 milliseconds. The VEP (i.e., the difference between the minimum and maximum potentials observed after each microburst) is noticeably improved in the trace 340 when compared with the VEP of the trace 320.

[0066] A trace 350 depicts the average potential (after 20 microbursts) measured in the monkey thalamus while a pulse burst having microbursts of three pulses each was applied to the vagus nerve. The inter-microburst interval was about 4 seconds and the interpulse interval was about 3 milliseconds. The VEP is noticeably improved in the trace 350 when compared with the VEP of the trace 340.

[0067] A trace 360 depicts the average potential (after 20 microbursts) measured in the monkey thalamus while a pulse burst having microbursts of four pulses each was applied to the vagus nerve. The inter-microburst interval was about 4 seconds and the interpulse interval was about 3 milliseconds. The VEP is noticeably improved in the trace 360 when compared with the VEP of the trace 350.

[0068] Referring to FIG. 4B, the effect of the interpulse interval on the VEP is illustrated. Traces 500, 510, 520, 530, and 540 depict the average potential (after 20 microbursts) measured in the monkey thalamus while a pulse burst having microbursts of two pulses each, separated by an inter-microburst interval of 4 sec. was applied to the vagus nerve. The interpulse intervals were about 40 milliseconds, about 20 milliseconds, about 10 milliseconds, about 6.7 milliseconds, and about 3 milliseconds for the traces 500, 510, 520, 530, and 540, respectively. The VEP is barely visible in the trace 500. The VEP is noticeably improved in the trace 510 when compared with the VEP of the trace 500. The VEP is noticeably improved in the trace 520 when compared with the VEP of the trace 510. The VEP is noticeably improved in the trace 530 when compared with the VEP of the trace 520. However, the VEP in the trace 540 is noticeably less than the VEP 534 of the trace 530.

[0069] Referring to FIG. 4C, the effect of the inter-microburst interval on the VEP is illustrated. Traces 600, 610, 620, 630, and 640 depict the average potential (after 20 microbursts) measured in the monkey thalamus while a pulse burst having microbursts of two pulses each, the pulses being separated by an interpulse interval of 6.7 milliseconds. was applied to the vagus nerve. The inter-microburst intervals corresponded to the microbursts occurring at a microburst frequency of about 10 Hz, about 3 Hz, about 1 Hz, about 0.3 Hz, and about 0.25 Hz for the traces 600, 610, 620, 630, and 640, respectively. The VEP is barely visible in the trace 600. Because the inter-microburst internal was sufficiently short, the trace 600 shows a second microburst artifact 606 to the right of the first microburst artifact 602. The VEP is noticeably improved in the trace 610 when compared with the VEP of the trace 600. The VEP is noticeably improved in the trace 620 when compared with the VEP of the trace 610. The VEP is noticeably improved in the trace 630 when compared with the VEP of the trace 620. However, the VEP in the trace 640 is noticeably less than the VEP in the trace 630.

[0070] As depicted in FIG. 4A-4C, the VEP is enormously enhanced (resulting in eVEP) and optimized by using a microburst of pulses (two or more, FIG. 4A) at appropriate interpulse intervals (in this case, 6.7 milliseconds was optimal for the first interpulse interval, shown in FIG. 4B) and at a inter-microburst interval (i.e., microburst frequency) that approximates the R-R cycle (i.e., the frequency at which the R wave portion appears in the ECG trace) of the monkey (in this case, about 0.3 Hz, as shown in FIG. 4C).

[0071] The experimental results depicted in FIG. 3D-3F and 4A-4C were obtained using a pulse burst including microbursts that were not synchronized with the cardiac cycle. In additional experiments, the effect of synchronizing the pulse bursts with the cardiac cycle was shown. Specifically, a single pulse was delivered at various times following every third R-wave. The VEP values obtained were then correlated with respiration. With respect to synchronization with the cardiac cycle, the experiments showed that the largest VEP was obtained when the pulse was delivered within 250 milliseconds after the initiation of a breath (which is accompanied by a decrease in the R-R interval). With respect to the delay period, the experiments showed that the greatest improvement in the VEP was obtained when the pulse was delivered about 400 milliseconds after the R-wave.

[0072] Additionally, the experimental data showed that by timing the pulse properly, an improvement in efficacy on the order of a factor of ten was obtained. Specifically, when the pulse was delivered about 0.5 seconds to about 1.0 second following the initiation of respiration and within 50 milliseconds following the R-wave, the VEP had a peak-to-peak amplitude of about 0.2 mV to about 0.4 mV. In contrast, when the pulse was delivered about 250 milliseconds after the initiation of inspiration and about 400 milliseconds following the R-wave, the VEP had a peak-to-peak amplitude of about 1.2 mV to about 1.4 mV. At maximum, this corresponds to about a seven-fold improvement in the VEP. These data show that by synchronizing the stimulation with respect to the cardiorespiratory cycles of the monkey, the efficacy of the stimulus pulse can be greatly improved over that of asynchronous stimulus delivery. These measurements were made in a monkey under deep anesthesia. Consequently, those of ordinary skill would expect an even greater effect in an awake human.

[0073] The use of pairs of pulses is a standard physiological tool for producing central responses by stimulation of small-diameter afferent fibers. However, according to the present invention, a pulse burst including microbursts of pulses having an appropriate sequence of interpulse intervals enormously enhances the effect of VNS. By selecting the appropriate signal parameters (e.g., pulse width, pulse frequency, interpulse interval(s), microburst frequency, microburst duration, number of pulses in the microbursts, etc.), the exogenous electrical signal applied to the vagus nerve may comprise a series of microbursts that each provide an eVEP.

[0074] As illustrated in FIG. 4A and 3E, a microburst duration greater than about 10 milliseconds (corresponding to 4 pulses having an interpulse interval of about 3 milliseconds.) produces a maximal eVEP in the thalamus of the monkey and an interpulse interval of about 6 milliseconds to about 9 milliseconds produces maximal facilitation by the first pulse of the second pulse. Accordingly, a brief microburst of pulses with a total duration of about 10 milliseconds to about 20 milliseconds and having an initial interpulse interval of about 6 milliseconds to about 9 milliseconds and subsequent intervals of similar or longer duration may produce an optimal VEP. This is because such microbursts of pulses simulate the pattern of naturally occurring action potentials in the small-diameter afferent vagal fibers that elicit the central response that the present enhanced and optimized therapy is most interested in evoking (see below). Selection of an appropriate inter-microburst interval to separate one microburst from the next may be performed experimentally, although as previously noted, a period of at least 100 milliseconds (preferably at least 500 milliseconds, and more preferably at least one second) and at least equal to the microburst duration may be desirable.

[0075] The most effective sequence of interpulse intervals will vary with the patient's HRV (cardiac and respiratory timing) and also between individual patients, and thus, in some embodiments, the parameters of the exogenous electrical signal, such as the number of pulses in a microburst, the interpulse interval(s), the inter-microburst interval(s), the duration of the pulse burst, the delay period(s) between each QRS wave and a microburst, the current amplitude, the QRS waves of the cardiac cycle after which a microburst will be applied, the pulse width, and the like may be optimized for each patient. As a standard microburst sequence for initial usage, a microburst of 2 or 3 pulses having an interpulse interval of about 5 milliseconds to about 10 milliseconds may be used to approximate the short burst of endogenous post-cardiac activity.

[0076] The inter-microburst interval may be determined empirically by providing microbursts with a steadily decreasing inter-microburst interval until the eVEP begins to decline. In some embodiments, the interpulse interval varies between the pulses. For example, the interpulse interval may increase between each successive pulse in the microburst, simulating the pattern of a decelerating post-synaptic potential, as illustrated in FIG. 1. In alternative embodiments, the interpulse intervals may decrease between each successive pulse in the microburst, or may be randomly determined within a preselected range, e.g., about 5 milliseconds to about 10 milliseconds. Alternatively, the interpulse interval may remain constant between successive pulses in the microburst (i.e., providing a simple pulse train). Further, in a method described below, the interpulse intervals may be specified between each successive pair of pulses using the VEP determined by an EEG. These modifications to the conventional VNS methodology produce a significant enhancement of VNS efficacy that is applicable to all VNS protocols and to many different medical conditions, including disorders of the nervous system.

[0077] As noted above, the stimulation parameters (e.g., interpulse interval(s), inter-microburst interval(s), number of pulses per microburst, etc.) may be individually optimized for each patient. The optimization is accomplished by using surface electrodes to detect a far-field VEP, originating in the thalamus and other regions of the forebrain, and varying the stimulus parameters to maximize the VEP detected. As illustrated in FIG. 5, standard EEG recording equipment 700 and a 16-lead or a 25-lead electrode placement 710 of the EEG surface electrodes 712, such as that typically used clinically for recording somatosensory or auditory evoked potentials, enables the VEP present in the patient's forebrain to be detected, using VNS stimulus microburst timing to synchronize averages of about 8 epochs to about 12 epochs. The EEG recording equipment 700 may be used to produce continuous EEG waveforms 720 and recordings 730 thereof. By testing the effects of varying the parameters of the exogenous electrical signal, the VEP can be optimized for each patient.

[0078] The exogenous electrical signal used to deliver VNS is optimized in individual patients by selecting stimulus parameters that produce the greatest effect as measured by EEG surface electrodes 740. The pulse current amplitude and pulse width is first optimized by measuring the size of the VEP elicited by individual pulses (and not microbursts). The number of pulses, interpulse intervals, and inter-microburst intervals are then optimized (using the current amplitude and pulse width determined previously) by measuring the magnitude of the VEP evoked by the microbursts, as well as the effects on de-synchronization in the continuous EEG recordings. It may be desirable to determine the number of pulses first and then determine the interpulse intervals between those pulses. In alternate embodiments, it may be desirable to determine the number of pulses first, followed by the microburst duration, and lastly, the interpulse intervals between the pulses.

[0079] Because the large eVEPs recorded in the thalamus, striatum, and insular cortex of the anesthetized monkey and shown in FIG. 4A-4C, are large enough that if evoked in a human patient, the eVEPs are observable in a standard EEG detected using electrodes adjacent to the human patient's scalp, the standard EEG may be used to indicate the effects of modifications to the signal parameters of the exogenous electrical signal. In this manner, the EEG may be used to optimize or tune the signal parameters of the exogenous electrical signal empirically. For a human patient, this method provides a safe and non-invasive way to customize the various signal parameters for the patient and/or the treatment of the patient's medical condition.

[0080] The eVEP recorded in the right thalamus and right striatum is significant for the anti-epileptic effects of VNS, whereas the eVEP recorded in the left insular cortex is most significant for the anti-depression effects of VNS. By using regional EEG localization on the right or left frontal electrodes, the signal parameters of the exogenous electrical signal may be optimized appropriately to achieve an eVEP in the appropriate region of the individual patient's brain. Further, the magnitude of the measured VEP may be appropriately tuned for the patient.

[0081] The optimal exogenous electrical signal parameters for eliciting eVEPs from these two areas (right thalamus/striatum and left insular cortex, respectively) may differ. Both eVEPs are identifiable using known EEG recording methods in awake human patients. Therefore, EEG recordings made using these methods may be used to evaluate the eVEP in the appropriate area. The EEG recording may be used to collect samples of the eVEP in the appropriate area(s) and those samples may be used easily for a parametric optimization, in a patient suffering from a disorder of the nervous system such as epilepsy or depression. Similarly, the exogenous electrical signal parameters used for HRV-synchronization may be selected based on their effects on the VEP and on the heartbeat-related evoked potential both of which may be measured using known noninvasive EEG recording methods that use EEG electrodes attached to the patient's scalp.

[0082] Referring to FIG. 6, an exemplary EEG is provided. A pair of traces 810 and 812 correspond to the potential present in the left striatum and left insular cortex and a pair of traces 820 and 822 correspond to the potential present in the left striatum and left insular cortex. While the same traces 810, 812, 820 and 822 depict the potential present in striatum and insular cortex, the potential in the striatum may be distinguished from the potential in the insular cortex by its timing. Experiments have shown that pulses applied to the vagus nerve reach the parafascicular nucleus in the thalamus in about 18 milliseconds and the basal portion of the ventral medial nucleus in about 34 milliseconds. The parafascicular nucleus then projects the stimulus to the striatum and the basal portion of the ventral medial nucleus projects the stimulus to the insular cortex. Consequently, the potential evoked by the pulse burst in the striatum will appear in the traces 810, 812, 820 and 822 before the potential evoked in the insular cortex. By analyzing the traces 810, 812, 820 and 822, the potential inside the striatum and/or the insular cortex may be observed and the signal parameter used to generate those potentials modified to enhance and/or optimize those potentials.

[0083] In FIG. 6, the strong VEP shown in traces 820 and 822 corresponding to the right thalamus and the right striatum (or basal ganglia) is associated with the anti-epileptic effects of VNS. As mentioned above, distinguishing the right thalamus from the right insular cortex may be accomplished by analyzing the timing of the eVEP observed in the traces 820 and 822. The strong VEP shown in traces 810 and 812 corresponding to the left thalamus and left insular cortex is associated with the anti-depression effects of VNS. Traces 830 and 832 in the central portion of the EEG depict a weak VEP in the thalamus. Because the EEG method described is noninvasive, it offers a safe and effective method of enhancing and/or optimizing the therapeutic effects of the exogenous electrical signal.

[0084] FIG. 7 illustrates one method of variable programming of the electrical signal generator 200 to optimize the eVEP in the right thalamus and striatum for epileptic patients, and in the left insula for patients suffering from depression. As shown in FIG. 7, a computer 900 may be coupled to and used to program the computer-controlled programming wand 800. The programming wand 800 may use radio frequency telemetry to communicate with the electrical signal generator 200 and program the burst duration, number of pulses in a microburst, interpulse interval(s), pulse frequency, microburst duration, inter-microburst interval, pulse width, and current amplitude of the exogenous electrical signal delivered by the electrical signal generator 200 to the vagus nerve of the patient. Using the programming wand 800, programming may be performed periodically or as needed on an implanted electrical signal generator 200. This provides the ability to continually optimize and change the exogenous electrical signal delivered by the electrical signal generator 200 depending on the EEG, and to respond to changes therein. Therefore, the present method of using one or more of the above referenced techniques, alone or in combination, significantly enhances and/or optimizes currently available VNS therapies. The invention is set out in the appended claims.

Claims

1. A computer readable medium programmed with instructions for simulating afferent action potentials or augmenting endogenous afferent activity within a vagus nerve of a patient when run on a device comprising a sensor (210A or 210B); an electrical signal generator (200) comprising a processor (230); and an electrode (220A or 220B), wherein the instructions, when executed by the processor (230), perform a method comprising: detecting a QRS wave portion (174) of a cardiac cycle and an R-R interval with the sensor (210A or 210B), where the R-R interval is the amount of time between two successive R wave portions (176) of the cardiac cycle; **characterized in that** the method comprises generating a pulsed electrical signal (130) with the electrical signal generator (200) on shortening R-R intervals during heart rate variability (HRV), such that a signal is only generated on a selected R-wave (176) having an R-R interval less than the preceding R-R interval, or less than a moving average for several R-R intervals, the pulsed electrical signal (130) comprising a series of microbursts (170); and in response to the detection of the QRS wave portion (174) of a cardiac cycle and the R-R interval, delivering the pulsed electrical signal (130) via the electrode (220A or 220B) to the vagus nerve of a patient, wherein the pulsed electrical signal (130) is configured to simulate afferent action potentials or augment endogenous afferent activity within the vagus nerve of the patient.

2. The computer readable medium of claim 1, wherein the method performed by the instructions when executed by the processor (230) further comprises determining the duration of each of the interpulse intervals.

3. The computer readable medium according to either claim 1 or 2, wherein the method performed by the instructions, when executed by the processor (230), further comprises:

   analyzing an EEG of the patient's brain created during the delivery of the pulsed electrical signal (130) to the vagus nerve of the patient to determine the vagal evoked potential observed in a selected structure of the brain; and modifying the value of a signal (130) parameter based on the vagal evoked potential observed in the selected structure of the brain to modify the vagal evoked potential observed therein.

4. The computer readable medium according to claim 3, wherein the selected structure of the brain includes a region selected from the group consisting of the thalamus, the striatum, the insular cortex, and combinations thereof.

5. The computer readable medium according to claim 4, wherein the signal parameter is a parameter selected from the group consisting of a pulse width, a pulse frequency, the interpulse interval between two of the pulses of a microburst (170), a frequency of the microbursts (170), the number of microbursts (170) in the pulsed electrical signal (130), the duration of the electrical signal (130), the number of pulses (182, 184, 186, 188) in the microbursts (170), and combinations thereof.

6. The computer readable medium according to any one of claims 1-5, wherein the series of microbursts (170) is generated after the elapse of a delay period (Di, D2, D3) following detection of the selected R-wave (176).

7. The computer readable medium according to any one of claims 1-6, wherein each microburst (170) of the pulsed electrical signal (130) has a duration of less than about one second.

8. The computer readable medium according to any one of claims 1-7, wherein the duration of each microburst (170) is less than about 100 milliseconds.

9. The computer readable medium according to any one of claims 1-8, wherein the interpulse interval between the electrical pulses (182, 184, 186, 188) of each microburst (170) ranges from about 3 milliseconds to about 10 milliseconds.

10. The computer readable medium according to any one of claims 1-9, wherein each microburst (170) comprises electrical pulses (182, 184, 186, 188) having a pulse width of from about 50 microseconds to about 1000 microseconds, and having a pulse current amplitude of from about 0.25 mA to about 8 mA.

11. The computer readable medium according to any one of claims 1-10, wherein the pulses (182, 184, 186, 188) of each microburst (170) of the pulsed electrical signal (130) are spaced to simulate endogenous afferent activity occurring at a particular time in the cardiac signal.

12. The computer readable medium according to any one of claims 1-11, wherein the pulsed electrical signal (130) comprises a plurality of microbursts (170), wherein the pulses (182, 184, 186, 188) of each microburst (170) are spaced to simulate endogenous afferent activity occurring at a particular time during inspiration of air by the lungs.

13. The computer readable medium according to any one of claims 1-12, wherein the pulsed electrical signal (130) comprises a plurality of microbursts (170), wherein the plurality of microbursts (170) are spaced to simulate endogenous afferent activity occurring at a particular time in the cardiac signal.

14. The computer readable medium according to any one of claims 1-13, wherein the pulsed electrical signal (130) comprises a plurality of microbursts (170), wherein the plurality of microbursts (170) are spaced to simulate endogenous afferent activity occurring at a particular time during inspiration of air by the lungs.

Patentansprüche

1. Computerlesbares Medium, das mit Anweisungen programmiert wurde, um afferente Aktionspotentiale zu simulieren oder endogene afferente Aktivität in einem Vagusnerv eines Patienten zu erhöhen, wenn es auf einer Vorrichtung ausgeführt wird, umfassend einen Sensor (210A oder 210B); einen elektrischen Signalgenerator (200), umfassend einen Prozessor (230); und eine Elektrode (220A oder 220B), wobei die Anweisungen, wenn sie durch den Prozessor (230) ausgeführt werden, ein Verfahren durchführen, das umfasst: Detektieren eines QRS-Wellenabschnitts (174) des Herzzyklus und eines R-R-Intervalls mit dem Sensor (210A oder 210B), wobei das R-R-Intervall die Zeitmenge zwischen zwei aufeinanderfolgenden R-Wellenabschnitten (176) des Herzzyklus ist; **dadurch gekennzeichnet, dass** das Verfahren das Erzeugen eines gepulsten elektrischen Signals (130) mit dem elektrischen Signalgenerator (200) auf verkürzten R-R-Intervallen während der Herzfrequenzvariabilität (HRV) umfasst, sodass ein Signal nur auf einer ausgewählten R-Welle (176) erzeugt wird, die ein R-R-Intervall aufweist, das kleiner als das vorhergehende R-R-Intervall oder kleiner als ein sich bewegender Durschnitt für mehrere R-R-Intervalle ist, wobei das gepulste elektrische Signal (130) eine Reihe von Mikrobursts (170) umfasst; und als Reaktion auf die Detektion des QRS-Wellenabschnitts (174) eines Herzzyklus und des R-R-Intervalls, Zuführen des gepulsten elektrischen Signals (130) über die Elektrode (220A oder 220B) an den Vagusnerv eines Patienten, wobei das gepulste elektrische Signal (130) konfiguriert ist, um afferente Aktionspotentiale zu simulieren oder endogene afferente Aktivität im Vagusnerv des Patienten zu erhöhen.

2. Computerlesbares Medium nach Anspruch 1, wobei das Verfahren, das durch die Anweisungen ausgeführt wird, wenn es durch den Prozessor (230) ausgeführt wird, ferner ein Bestimmen der Dauer von jedem der Interpulsintervalle umfasst.

3. Computerlesbares Medium nach Anspruch 1 oder 2, wobei das durch die Anweisungen durchgeführte Verfahren, wenn ausgeführt durch den Prozessor (230), ferner umfasst:

Analysieren eines EEGs des Gehirns des Patienten, das während der Zuführung des gepulsten elektrischen Signals (130) an den Vagusnerv des Patienten erzeugt wurde, um das evozierte vagale Potential zu bestimmen, das in einer ausgewählten Gehirnstruktur beobachtet wird; und
Modifizieren des Werts eines Parameters eines Signals (130) auf der Grundlage des evozierten vagalen Potentials, das in der ausgewählten Gehirnstruktur beobachtet wird, um das darin beobachtete evozierte vagale Potential zu modifizieren.

4. Computerlesbares Medium nach Anspruch 3, wobei die ausgewählte Gehirnstruktur einen Bereich beinhaltet, der aus der Gruppe ausgewählt ist, die aus dem Thalamus, dem Striatum, der Inselrinde und Kombinationen davon besteht.

5. Computerlesbares Medium nach Anspruch 4, wobei der Signalparameter ein Parameter ist, der aus der Gruppe ausgewählt ist, die aus einer Impulsbreite, einer Impulsfrequenz, der Impulslücke zwischen zwei der Impulse eines Mikrobursts (170), einer Frequenz der Mikrobursts (170), der Anzahl der Mikrobursts (170) in dem gepulsten elektrischen Signal (130), der Dauer des elektrischen Signals (130), der Anzahl von Impulsen (182, 184, 186, 188) in den Mikrobursts (170) und Kombinationen davon besteht.

6. Computerlesbares Medium nach einem der Ansprüche 1 bis 5, wobei die Reihe von Mikrobursts (170) nach dem Verstreichen einer Verzögerungsperiode (D1, D2, D3) im Anschluss an die Detektion der ausgewählten R-Welle (176) erzeugt wird.

7. Computerlesbares Medium nach einem der Ansprüche 1 bis 6, wobei jeder Mikroburst (170) des gepulsten elektrischen Signals (130) eine Dauer von weniger als ungefähr einer Sekunde aufweist.

8. Computerlesbares Medium nach einem der Ansprüche 1 bis 7, wobei die Dauer von jedem Mikroburst (170) weniger als ungefähr 100 Millisekunden beträgt.

9. Computerlesbares Medium nach einem der Ansprüche 1 bis 8, wobei das Interpulsintervall zwischen den elektrischen Impulsen (182, 184, 186, 188) jedes Mikrobursts (170) im Bereich von ungefähr 3 Millisekunden bis ungefähr 10 Millisekunden liegt.

10. Computerlesbares Medium nach einem der Ansprüche 1 bis 9, wobei jeder Mikroburst (170) elektrische Impulse (182, 184, 186, 188) umfasst, die eine Impulsbreite von ungefähr 50 Mikrosekunden bis ungefähr 1000 Mikrosekunden aufweisen, und die eine Impulsstromamplitude von ungefähr 0,25 mA bis ungefähr 8 mA aufweisen.

11. Computerlesbares Medium nach einem der Ansprüche 1 bis 10, wobei die Impulse (182, 184, 186, 188) jedes Mikrobursts (170) des gepulsten elektrischen Signals (130) beabstandet sind, um eine endogene afferente Aktivität zu simulieren, die zu einer bestimmten Zeit im Herzsignal auftritt.

12. Computerlesbares Medium nach einem der Ansprüche 1 bis 11, wobei das gepulste elektrische Signal (130) eine Vielzahl von Mikrobursts (170) umfasst, wobei die Impulse (182, 184, 186, 188) jedes Mikrobursts (170) beabstandet sind, um eine endogene afferente Aktivität zu simulieren, die zu einer bestimmten Zeit während der Inspiration von Luft durch die Lungen auftritt.

13. Computerlesbares Medium nach einem der Ansprüche 1 bis 12, wobei das gepulste elektrische Signal (130) eine Vielzahl von Mikrobursts (170) umfasst, wobei die Vielzahl von Mikrobursts (170) beabstandet sind, um eine endogene afferente Aktivität zu simulieren, die zu einem bestimmten Zeitpunkt im Herzsignal auftritt.

14. Computerlesbares Medium nach einem der Ansprüche 1 bis 13, wobei das gepulste elektrische Signal (130) eine Vielzahl von Mikrobursts (170) umfasst, wobei die Vielzahl von Mikrobursts (170) beabstandet sind, um endogene afferente Aktivität zu simulierten, die zu einem bestimmten Zeitpunkt während der Inspiration von Luft durch die Lungen auftritt.

Revendications

1. Support lisible par ordinateur programmé avec des instructions pour simuler des potentiels d'action afférents ou augmenter une activité afférente endogène d'un nerf vague d'un patient lors de son utilisation sur un dispositif comprenant un capteur (210A ou

210B) ;
un générateur de signal électrique (200) comprenant un processeur (230) ; et
une électrode (220A ou 220B), les instructions, lorsqu'elles sont exécutées par le processeur (230), exécutant un procédé comprenant :

la détection d'une partie d'onde QRS (174) d'un cycle cardiaque, et d'un intervalle R-R avec un capteur (210A ou 210B), l'intervalle R-R étant la quantité de temps s'écoulant entre deux parties d'onde R successives (176) du cycle cardiaque ;
caractérisé en ce que la méthode comprend la génération d'un signal électrique pulsé (130) avec le générateur de signal électrique (200) lors de la réduction des intervalles R-R au cours d'une variabilité de la fréquence cardiaque (HRV), de sorte que le signal ne soit généré que sur une onde R sélectionnée (176) dont l'intervalle R-R est inférieur à l'intervalle R-R précédent, ou inférieur à une moyenne mobile pour plusieurs intervalles R-R, le signal électrique pulsé (130) comprenant une série de micro-rafales (170) ; et
en réponse à la détection d'une partie d'onde QRS (174) d'un cycle cardiaque, et de l'intervalle R-R, l'émission du signal électrique pulsé (130) à travers l'électrode (220A ou 220B) au nerf vague d'un patient, le signal électrique pulsé (130) étant configuré pour simuler des potentiels d'action afférents ou augmenter une activité afférente endogène au sein du nerf vague du patient.

2. Support lisible par ordinateur selon la revendication 1, lorsqu'elle est exécutée par le processeur (230), la méthode mise en oeuvre par les instructions comprenant en outre la détermination de la durée de chacun des intervalles inter-impulsion.

3. Support lisible par ordinateur selon la revendication 1 ou 2, lorsqu'elle est exécutée par le processeur (230), la méthode mise en oeuvre par les instructions comprenant en outre :

l'analyse d'un électroencéphalogramme du cerveau du patient créé au cours de l'émission du signal électrique pulsé (130) au nerf vague du patient afin de déterminer le potentiel évoqué vagal observé dans une structure sélectionnée du cerveau ; et
la modification de la valeur d'un signal (130) à base de paramètre sur le potentiel évoqué vagal observé dans une structure sélectionnée du cerveau pour modifier le potentiel évoqué vagal observé dans celui-ci.

4. Support lisible par ordinateur selon la revendication 3, la structure sélectionnée du cerveau comprenant une région sélectionnée dans le groupe composé du thalamus, du striatum, du cortex insulaire, et de combinaisons de ceux-ci.

5. Support lisible par ordinateur selon la revendication 4, le paramètre de signal étant un paramètre sélectionné dans le groupe composé d'une largeur d'impulsion, d'une fréquence d'impulsion, de l'intervalle inter-impulsions entre deux des impulsions d'une série de micro-rafales (170), d'une fréquence des micro-rafales (170), du nombre de micro-rafales (170) dans le signal électrique pulsé (130), de la durée du signal électrique (130), du nombre d'impulsions (182, 184, 186, 188) dans les micro-rafales (170), et de combinaisons de ces derniers.

6. Support lisible par ordinateur selon une quelconque des revendications 1 à 5, la série de micro-rafales (170) étant générée après l'écoulement d'une période d'attente (Dl, D2, D3) suivie de la détection de l'onde R sélectionnée (176).

7. Support lisible par ordinateur selon une quelconque des revendications 1 à 6, chaque micro-rafale (170) du signal électrique pulsé (130) ayant une durée inférieure à environ une seconde.

8. Support lisible par ordinateur selon une quelconque des revendications 1 à 7, la durée de chaque micro-rafale (170) étant inférieure à environ 100 millisecondes.

9. Support lisible par ordinateur selon une quelconque des revendications 1 à 8, l'intervalle inter-impulsions entre les impulsions électriques (182, 184, 186, 188) de chaque micro-rafale (170) étant compris dans la plage allant d'environ 3 millisecondes à environ 10 millisecondes.

10. Support lisible par ordinateur selon une quelconque des revendications 1 à 9, chaque micro-rafale (170) comprenant des impulsions électriques (182, 184, 186, 188) dont la largeur d'impulsion est comprise entre environ 50 microsecondes et environ 1000 microsecondes, et l'amplitude de courant pulsé étant comprise entre environ 0,25 mA et environ 8 mA.

11. Support lisible par ordinateur selon une quelconque des revendications 1 à 10, les impulsions (182, 184, 186, 188) de chaque micro-rafale (170) du signal électrique pulsé (130) étant espacées pour simuler une activité afférente endogène survenant à un certain moment dans le signal cardiaque.

12. Support lisible par ordinateur selon une quelconque des revendications 1 à 11, le signal électrique pulsé

(130) comprenant une série de micro-rafales (170), les impulsions (182, 184, 186, 188) de chaque micro-rafale (170) étant espacées pour simuler une activité afférente endogène survenant à un certain moment au cours de l'aspiration d'air par les poumons.

13. Support lisible par ordinateur selon une quelconque des revendications 1 à 12, le signal électrique pulsé (130) comprenant une pluralité de micro-rafales (170), la pluralité de micro-rafales (170) étant espacée pour simuler une activité afférente endogène survenant à un certain moment au cours du signal cardiaque.

14. Support lisible par ordinateur selon une quelconque des revendications 1 à 13, le signal électrique pulsé (130) comprenant une pluralité de micro-rafales (170), la pluralité de micro-rafales (170) étant espacée pour simuler une activité afférente endogène survenant à un certain moment au cours d'une aspiration d'air par les poumons.

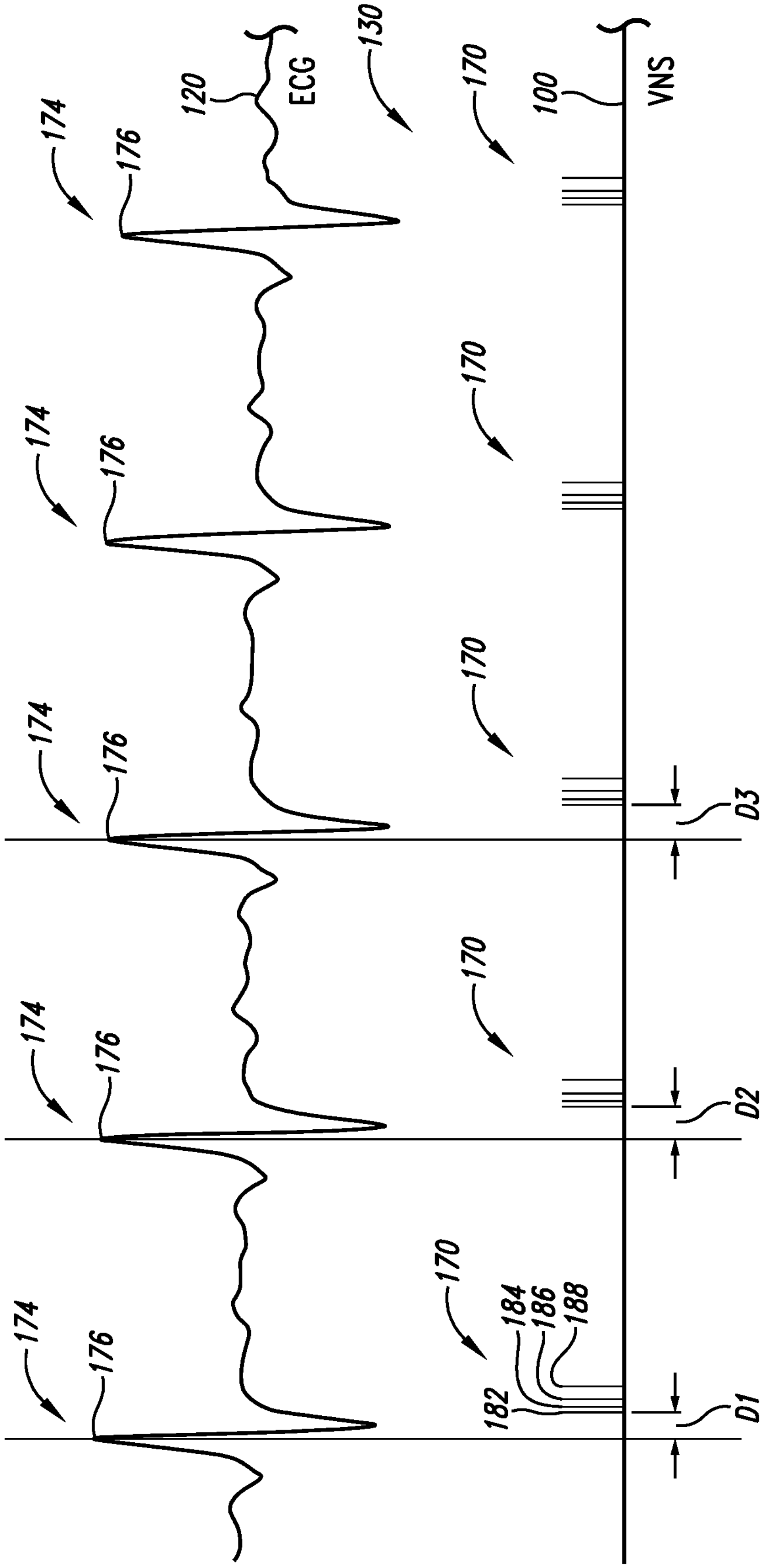


Fig. 1

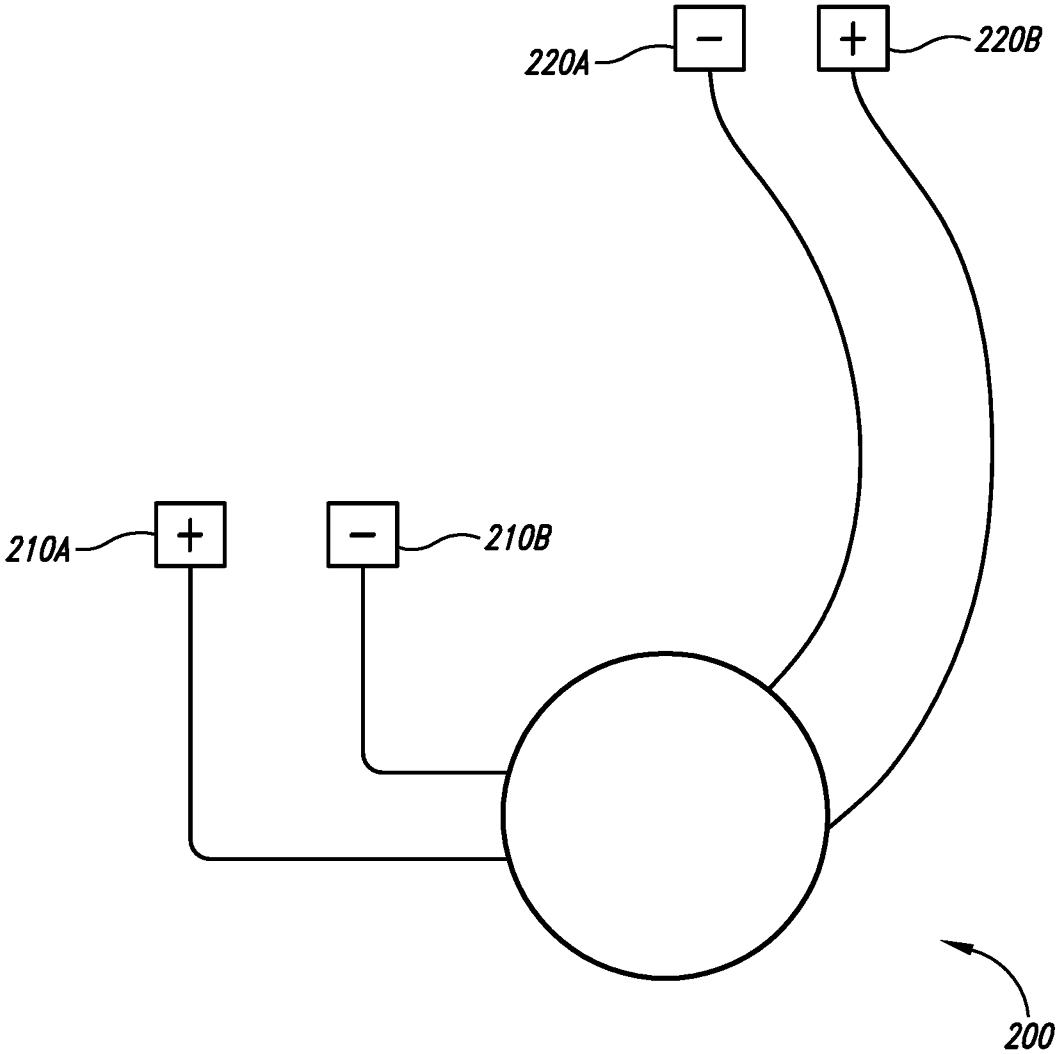


Fig. 2A

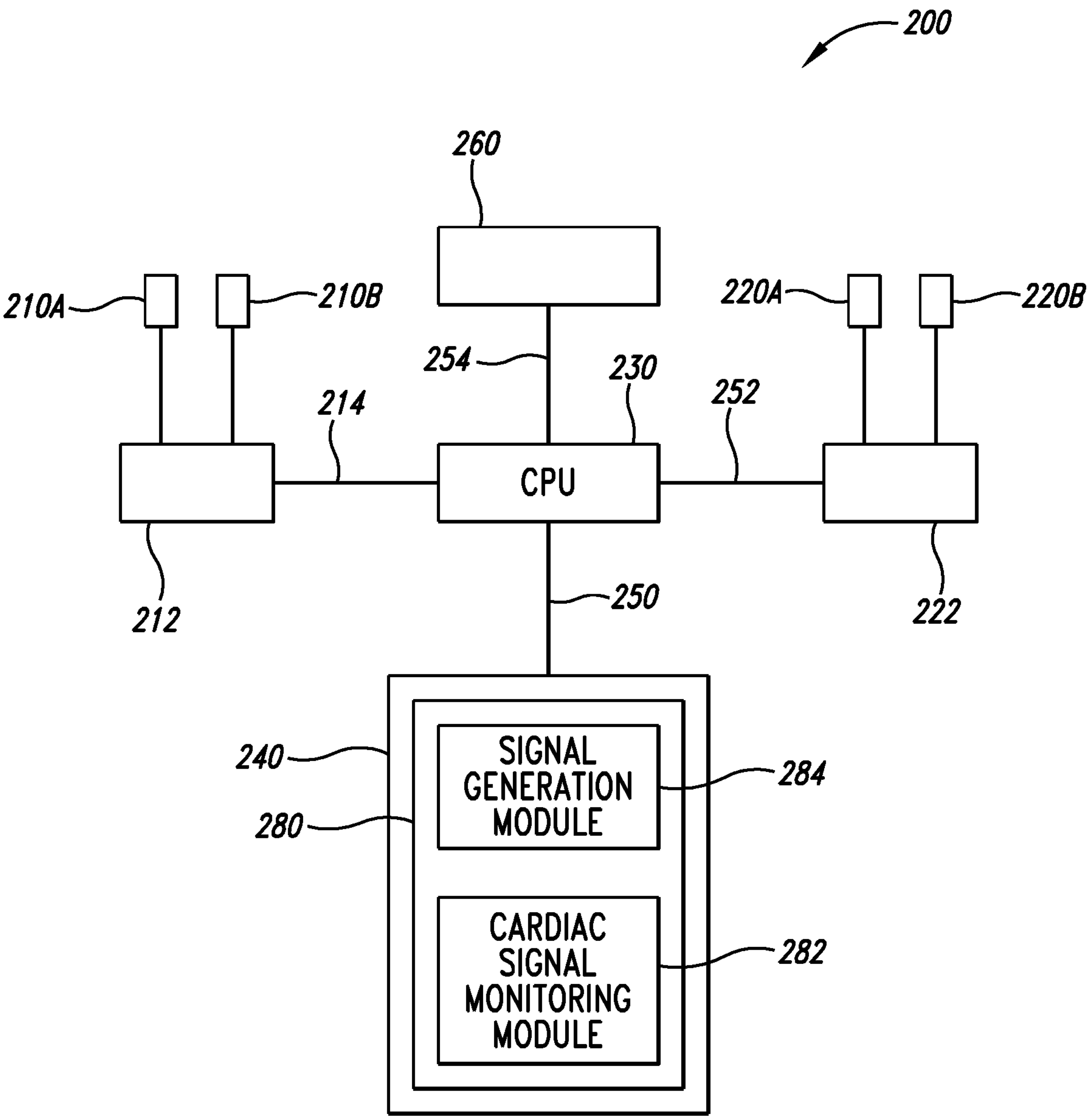

200
260
210A
210B
220A
220B
254
230
252
214
CPU
212
222
250
240
SIGNAL
GENERATION
MODULE
284
280
CARDIAC
SIGNAL
MONITORING
MODULE
282

Fig. 2B

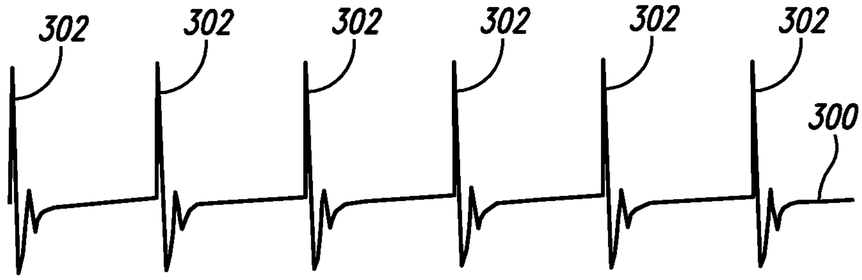


Fig. 3A

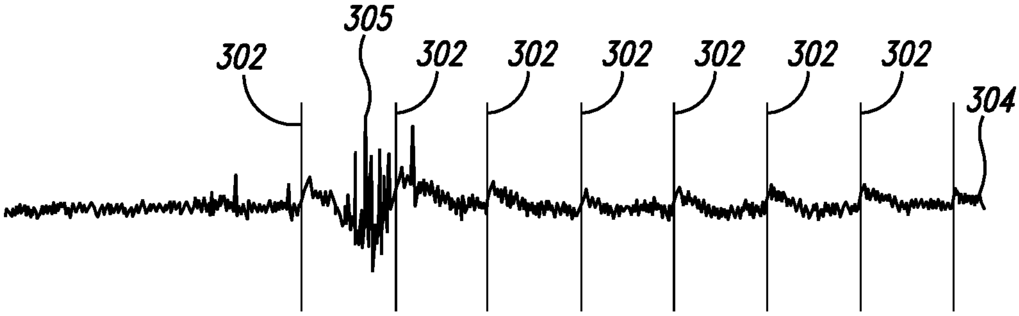


Fig. 3B

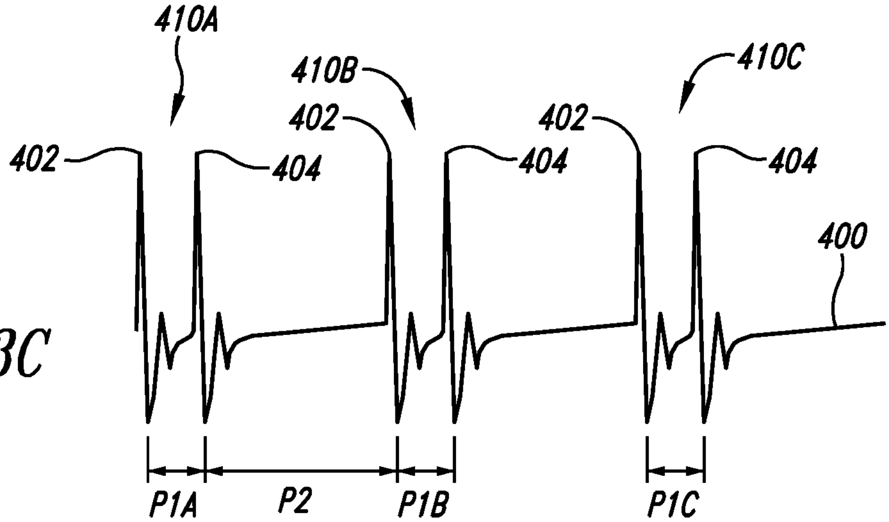


Fig. 3C

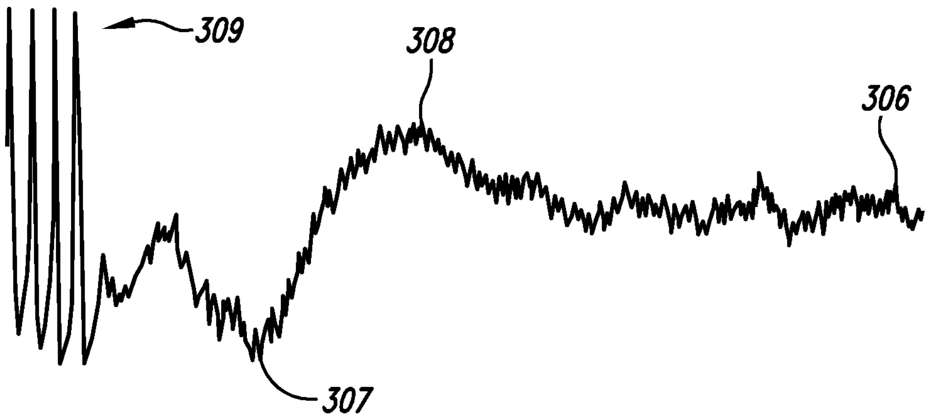
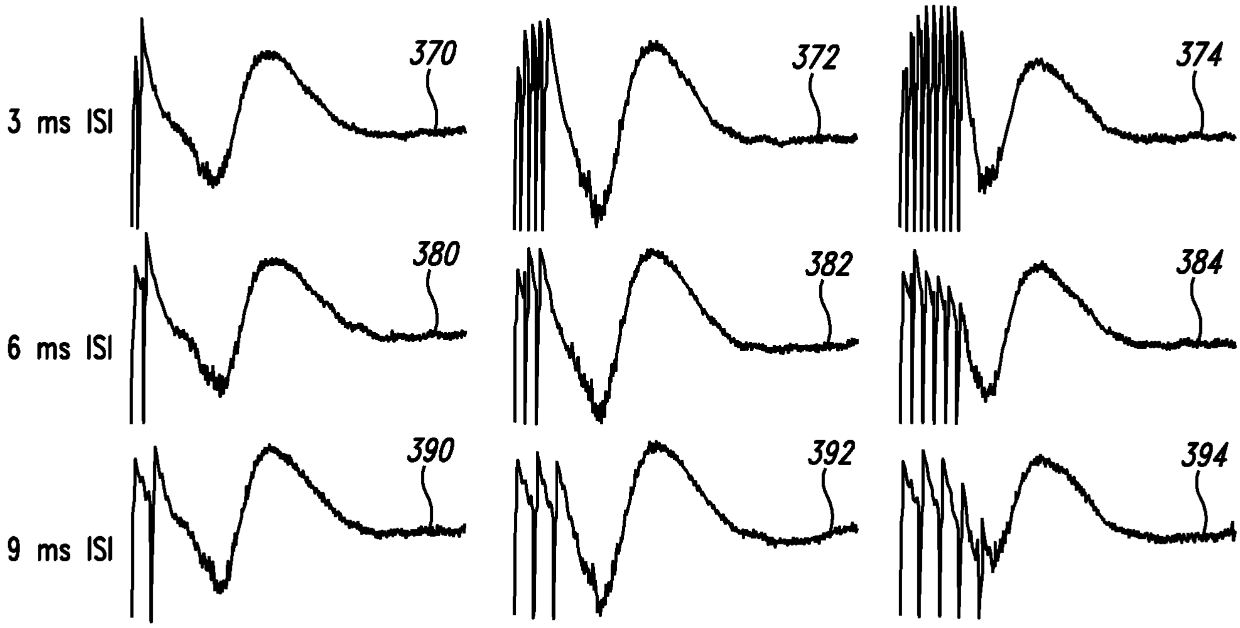

309
308
306
307

Fig. 3D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6 ms ISI
9 ms ISI
370
372
374
380
382
384
390
392
394

Fig. 3E

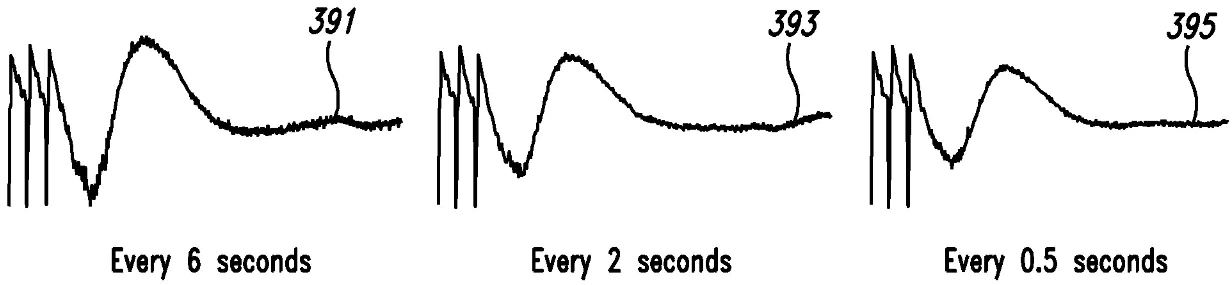

391
393
395
Every 6 seconds
Every 2 seconds
Every 0.5 seconds

Fig. 3F

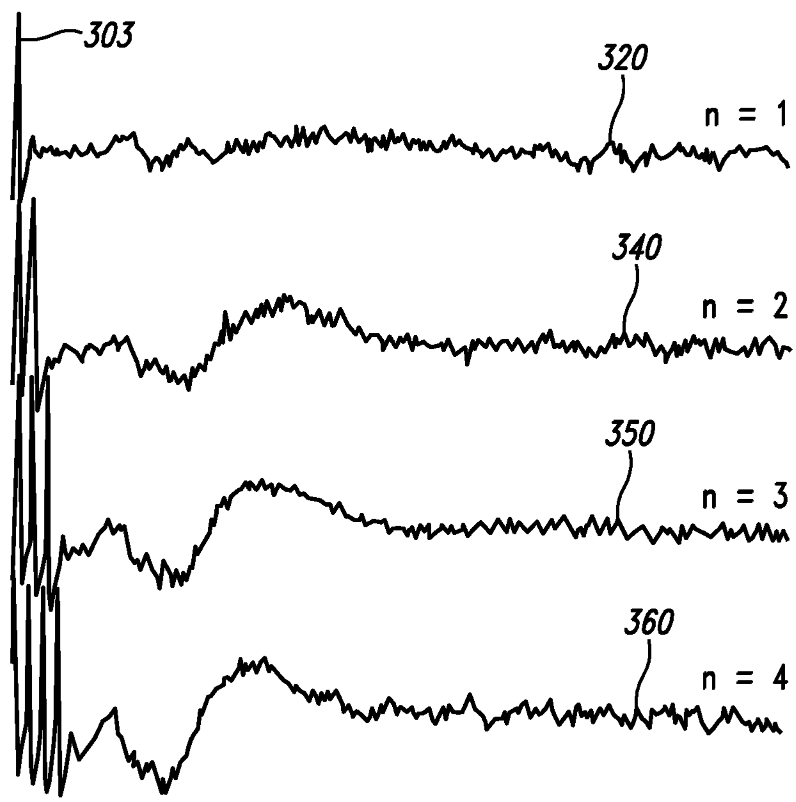
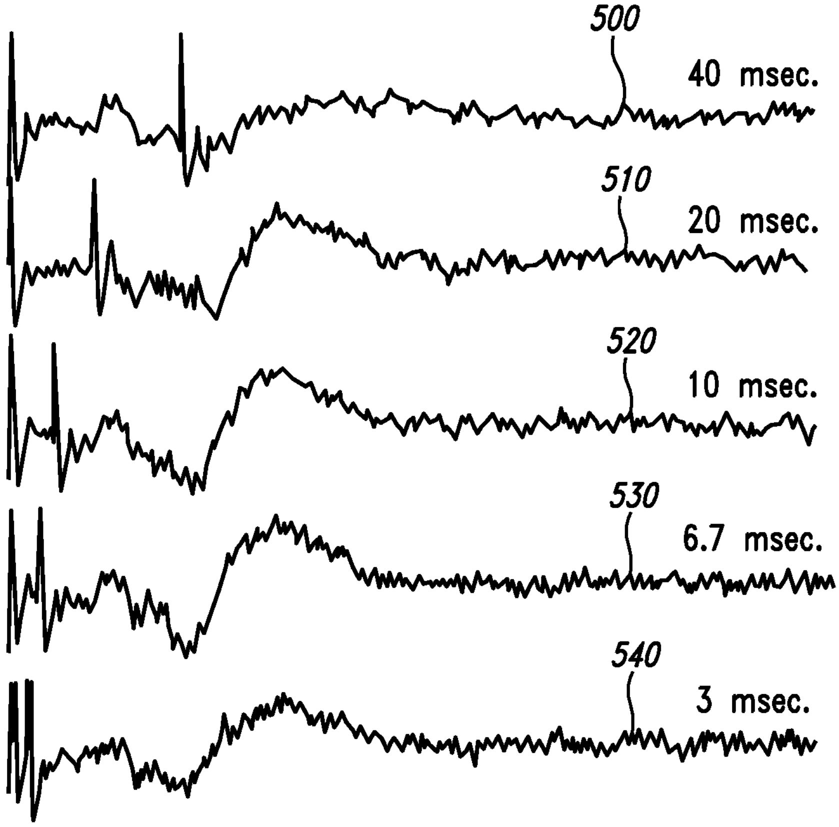

303
320
n = 1
340
n = 2
350
n = 3
360
n = 4

Fig. 4A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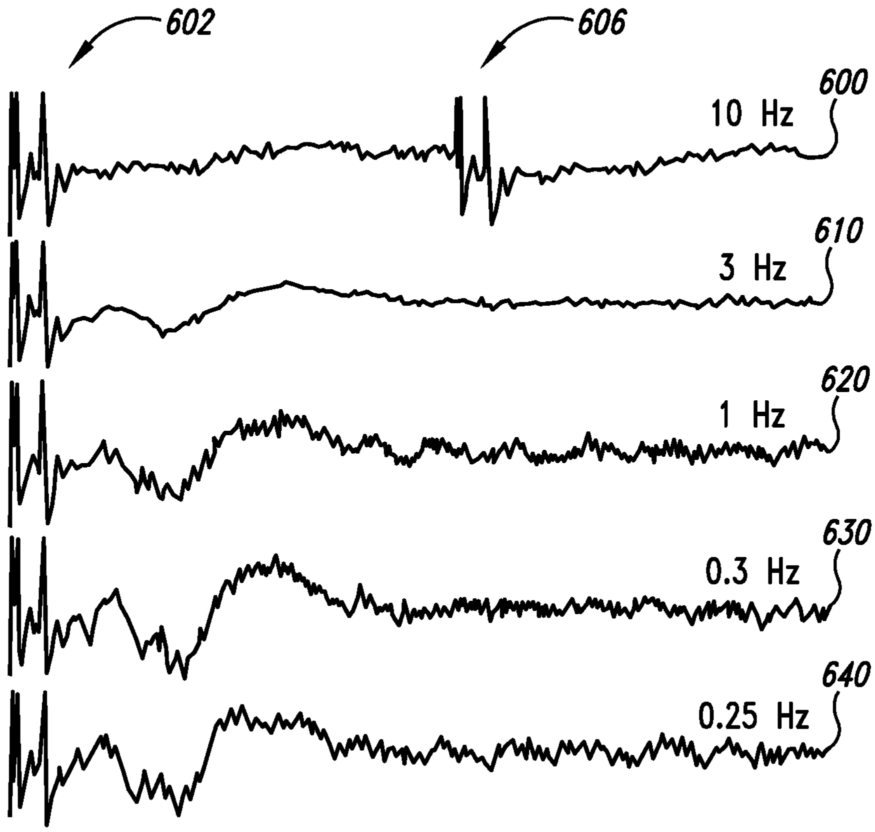
40 msec.
510
20 msec.
520
10 msec.
530
6.7 msec.
540
3 msec.

Fig. 4B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606
600
10 Hz
610
3 Hz
620
1 Hz
630
0.3 Hz
640
0.25 Hz

Fig. 4C

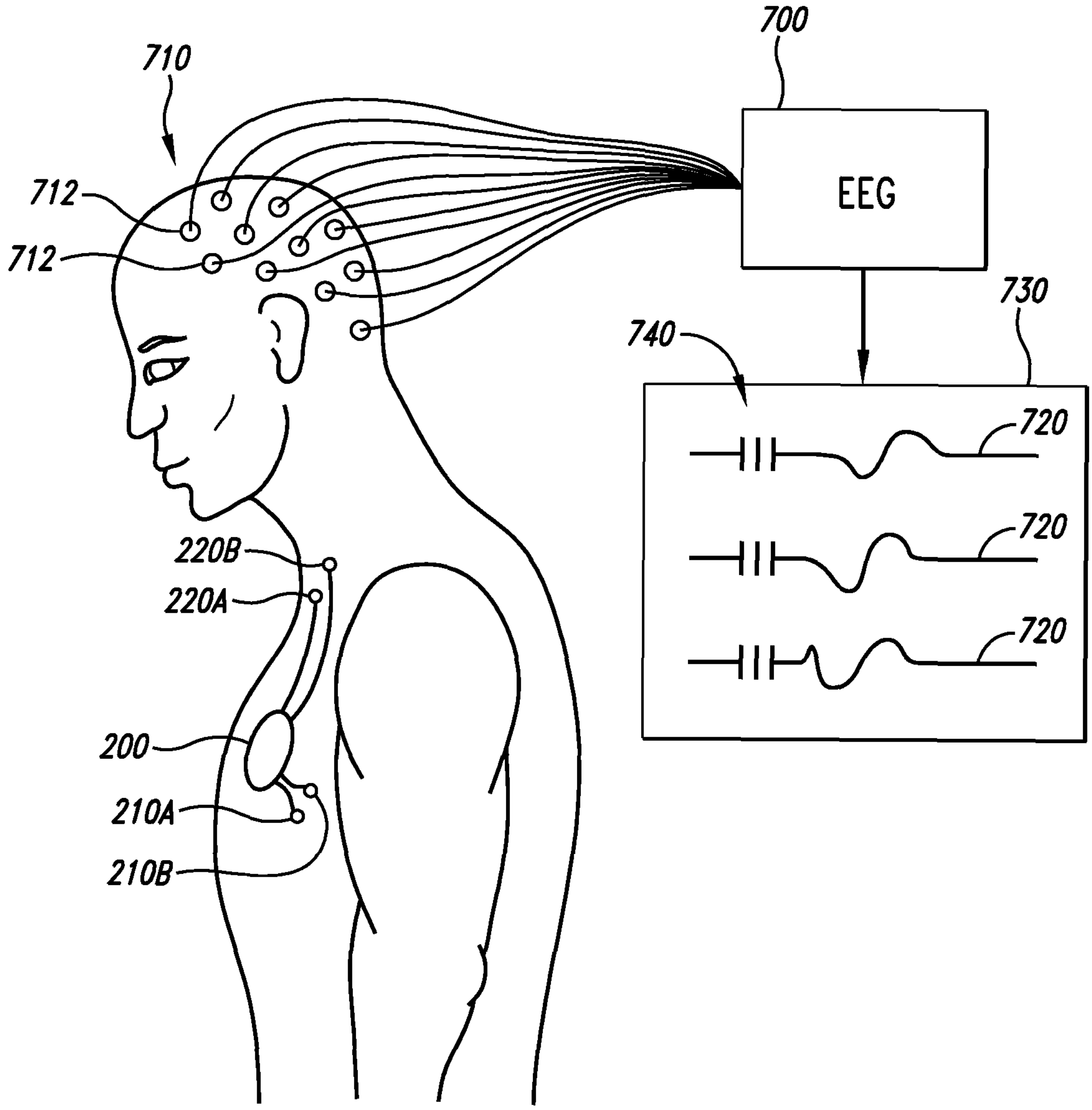

Fig. 5

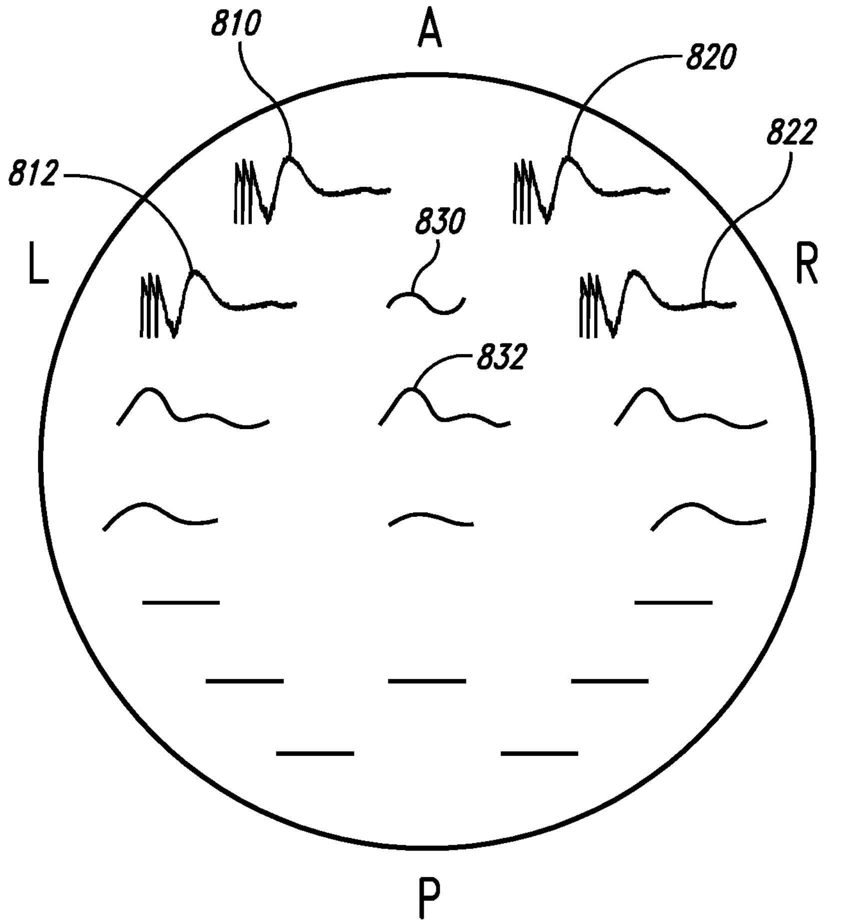

Fig. 6

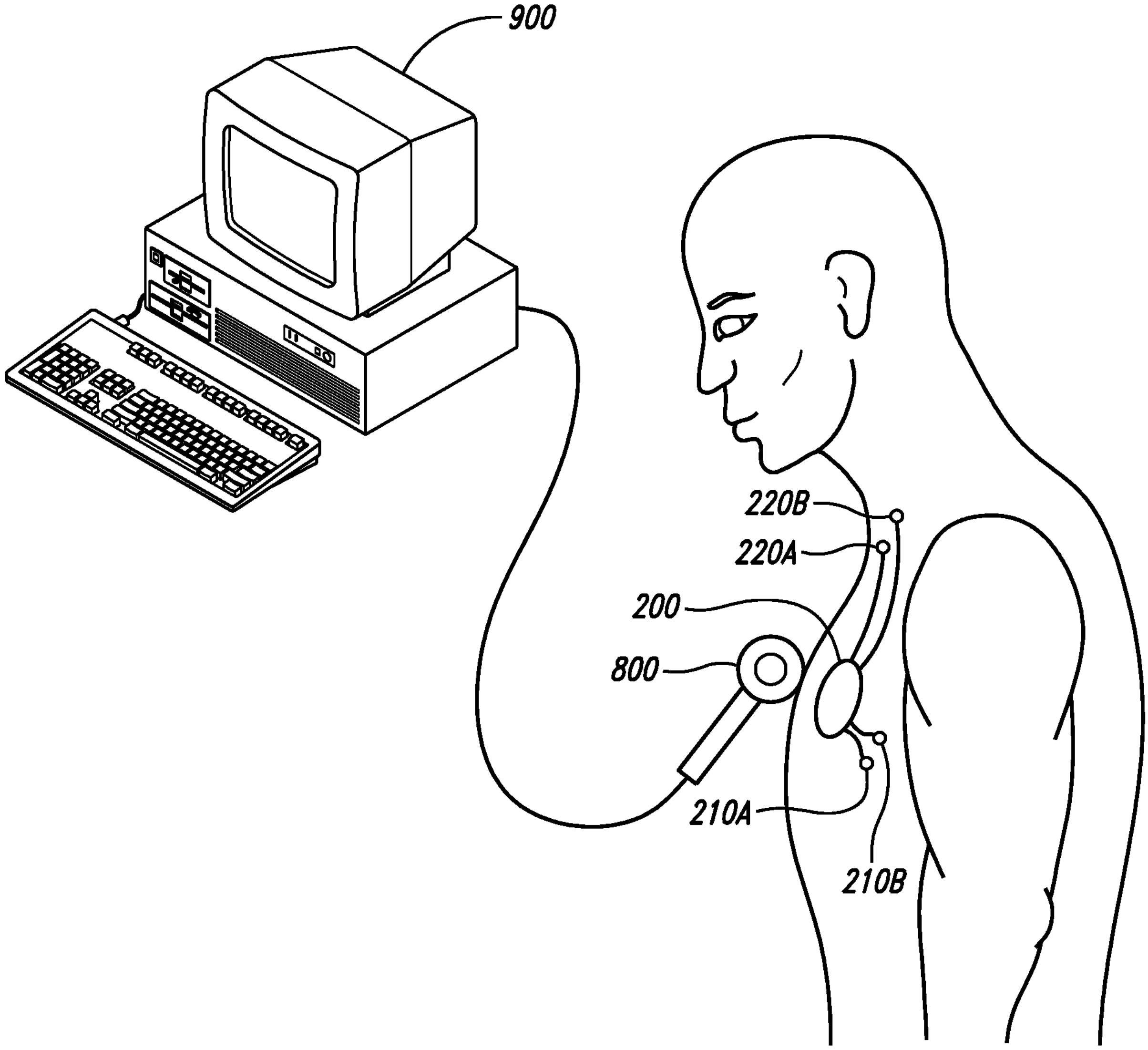

Fig. 7

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- US 2005267542 A **[0006]**

专利名称(译)	迷走神经刺激		
公开(公告)号	EP2918310B1	公开(公告)日	2018-05-30
申请号	EP2015161760	申请日	2007-03-29
申请(专利权)人(译)	卫生尊严		
当前申请(专利权)人(译)	卫生尊严		
[标]发明人	CRAIG ARTHUR D		
发明人	CRAIG, ARTHUR, D.		
IPC分类号	A61N1/36 A61N1/05 A61B5/0476 A61B5/00		
CPC分类号	A61N1/36139 A61B5/0476 A61B5/4094 A61N1/0551 A61N1/3605 A61N1/36053 A61N1/36064 A61N1/36082 A61N1/36114 A61N1/36178		
代理机构(译)	HUTTER，ANTON		
优先权	60/787680 2006-03-29 US		
其他公开文献	EP2918310A2 EP2918310A3		
外部链接	Espacenet		

摘要(译)

植入的电信号发生器向患者的迷走神经递送新的外源电信号。迷走神经将源自心脏和肺的动作电位传导到大脑的各种结构，从而在这些结构中引起迷走神经诱发电位。外源电信号模拟和/或增强源自患者心脏和/或肺的内源传入活动，从而增强脑的各种结构中的迷走神经诱发电位。外源电信号包括一系列电脉冲，这些电脉冲被组织或图案化成一系列微爆，每个微爆包括2到20个脉冲。在微爆流之间没有发送脉冲。每个微爆流可以与ECG的QRS波部分同步。在各种脑结构中增强的迷走神经诱发电位可用于治疗各种医学病症，包括癫痫和抑郁症。

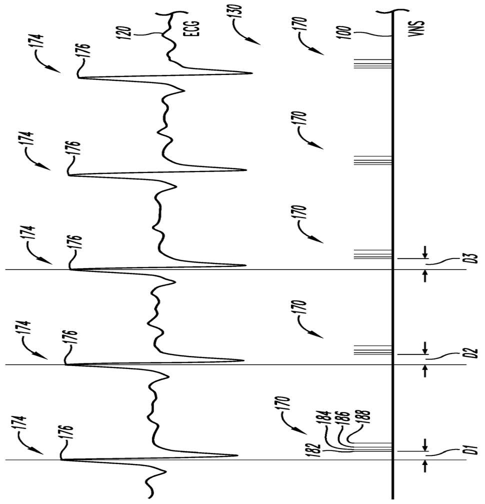

Fig. 1