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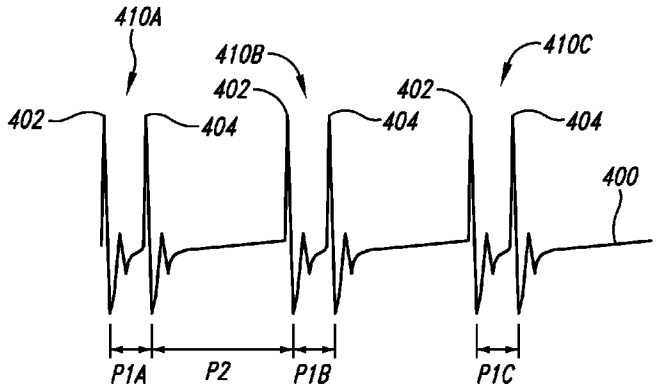
(54) **Title:** VAGUS NERVE STIMULATION METHOD



(57) **Abstract:** An implanted electrical signal generator delivers a novel exogenous electrical signal to a vagus nerve of a patient. The vagus nerve conducts action potentials originating in the heart and lungs to various structures of the brain, thereby eliciting a vagal evoked potential in those structures. The exogenous electrical signal simulates and/or augments the endogenous afferent activity originating from the heart and/or lungs of the patient, thereby enhancing the vagal evoked potential in the various structures of the brain. The exogenous electrical signal includes a series of electrical pulses organized or patterned into a series of microbursts including 2 to 20 pulses each. No pulses are sent between the microbursts. Each of the microbursts may be synchronized with the QRS wave portion of an ECG. The enhanced vagal evoked potential in the various structures of the brain may be used to treat various medical conditions including epilepsy and depression.

WO 2007/115118 A1

VAGUS NERVE STIMULATION METHOD

CROSS REFERENCE TO RELATED APPLICATION(S)

This application claims the benefit of U.S. Provisional Application No. 60/787,680, filed March 29, 2006.

The United States patent application entitled "Synchronization Of Vagus Nerve Stimulation With The Cardiac Cycle Of A Patient" by Arthur D. Craig and filed concurrently herewith is hereby incorporated herein by reference.

The United States patent application entitled "Microburst Electrical Stimulation Of Cranial Nerves For The Treatment Of Medical Conditions," by Arthur D. Craig and filed concurrently herewith is hereby incorporated herein by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

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

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

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).

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.

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.

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.

SUMMARY OF THE INVENTION

In one embodiment, the invention includes a method of treating a medical condition by detecting a portion of the QRS wave of the patient's cardiac signal and after detecting the portion of the QRS wave, delivering a microburst comprising 2 to 20 electrical pulses to the patient's vagus nerve. Each of the microbursts may have duration of less than about 100 milliseconds. In particular embodiments, the interpulse intervals separating the pulses are about 3 milliseconds to about 12 milliseconds. In alternate embodiments, the interpulse intervals are less than about 40 milliseconds. In various embodiments, the sum of the interpulse intervals is less than about 40 milliseconds, and in further embodiments, less than about 60 milliseconds. In further embodiments, the method includes waiting a predetermined delay period after the detection of the portion of the QRS wave before generating the microburst.

In another embodiment, the invention includes an exogenous electrical signal delivered to a patient's vagus nerve and adapted to treat a medical condition present in the patient by enhancing the vagal evoked potential in the patient's brain. The exogenous electrical signal includes a series of microbursts each having about 2 to about 20 electrical pulses. In some embodiments, the exogenous electrical signal includes a series of microbursts each having a duration less than about one second. The invention also includes an implantable device configured to apply the inventive exogenous electrical signal.

In further embodiments, the microbursts of the exogenous electrical signal may be synchronized with the R wave portion of the patient's cardiac cycle. In particular embodiments, each of the microbursts of the exogenous electrical signal occur after a selected R wave portion. In various embodiments, each of the microbursts occurs less than about 1000 milliseconds after the selected R wave portion. The pulses of the microbursts may be spaced to simulate the endogenous afferent activity occurring at a particular time in the cardiac cycle. Further, each of the microbursts may be delayed relative to the selected R wave portion to simulate the endogenous afferent activity occurring at a particular time in the cardiac cycle. In various embodiments, the delay has a duration less than about 500 milliseconds. In further embodiments, the delay has a duration less than about 1000 milliseconds.

In various embodiments, each of the microbursts occurs after an R-R interval (i.e., the amount of time between two successive R wave portions in the cardiac signal) having a duration that is shorter than the duration of the previous R-R interval. In further embodiments, the microbursts are delivered to the vagus nerve after the R wave portions occurring during inspiration but not after the R wave portions occurring during expiration.

The invention also includes a method of customizing the exogenous electrical signal to elicit a desired vagal evoked potential in a selected structure of the brain associated with a medical condition. The method includes determining a value of a signal parameter (e.g., pulse width, pulse frequency, an interpulse interval between two of the pulses of the microburst, microburst frequency, a number of microbursts of the series of microburst, a duration of the electrical signal, a number of pulses in the microbursts, etc.), generating an electrical signal having a series of microbursts of 2 to 20 electrical pulses each according to the signal parameter, delivering the electrical signal to the patient's vagus nerve, analyzing an EEG of the patient's brain created during the delivery of the electrical signal to determine the vagal evoked potential observed in the selected structure of the brain, and modifying the value of the signal parameter based on the vagal evoked potential observed in the selected structure of the brain to modify the vagal evoked potential observed therein. In various embodiments, the selected structure of the brain includes the thalamus, striatum, and/or insular cortex.

Embodiments of the invention also include 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.

The invention also includes embodiments wherein the patient manually triggers the generation and delivery of the inventive exogenous electrical signal to his/her vagus nerve.

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

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

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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 "P1B" 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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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).

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.

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.

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.

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.

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.

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 pre-selected 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.

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.

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.

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.

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.

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.

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.

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 non-invasive, it offers a safe and effective method of enhancing and/or optimizing the therapeutic effects of the exogenous electrical signal.

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.

Various embodiments of the invention are described above in the Detailed Description. While these descriptions directly describe the above embodiments, it is understood that those skilled in the art may conceive modifications and/or variations to the specific embodiments shown and described herein. Any such modifications or

variations that fall within the purview of this description are intended to be included therein as well. Unless specifically noted, it is the intention of the inventors that the words and phrases in the specification and claims be given the ordinary and accustomed meanings to those of ordinary skill in the applicable art(s).

The foregoing description of various embodiments of the invention known to the applicant at this time of filing the application has been presented and is intended for the purposes of illustration and description. The present description is not intended to be exhaustive nor limit the invention to the precise form disclosed and many modifications and variations are possible in the light of the above teachings. The embodiments described serve to explain the principles of the invention and its practical application and to enable others skilled in the art to utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. Therefore, it is intended that the invention not be limited to the particular embodiments disclosed for carrying out the invention.

While particular embodiments of the present invention have been shown and described, it will be obvious to those skilled in the art that, based upon the teachings herein, changes and modifications may be made without departing from this invention and its broader aspects and, therefore, the appended claims are to encompass within their scope all such changes and modifications as are within the true spirit and scope of this invention. Furthermore, it is to be understood that the invention is solely defined by the appended claims. It will be understood by those within the art that, in general, terms used herein, and especially in the appended claims (e.g., bodies of the appended claims) are generally intended as “open” terms (e.g., the term “including” should be interpreted as “including but not limited to,” the term “having” should be interpreted as “having at least,” the term “includes” should be interpreted as “includes but is not limited to,” etc.). It will be further understood by those within the art that if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of the introductory phrases "at least one" and "one or more" to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles "a" or "an" limits any particular claim containing such introduced claim recitation to inventions containing only one such recitation, even when the same claim includes the introductory phrases "one

or more" or "at least one" and indefinite articles such as "a" or "an" (e.g., “a” and/or “an” should typically be interpreted to mean “at least one” or “one or more”); the same holds true for the use of definite articles used to introduce claim recitations. In addition, even if a specific number of an introduced claim recitation *is* explicitly recited, those skilled in the art will recognize that such recitation should typically be interpreted to mean *at least* the recited number (e.g., the bare recitation of "two recitations," without other modifiers, typically means *at least* two recitations, or *two or more* recitations).

Accordingly, the invention is not limited except as by the appended claims.

CLAIMS

The invention claimed is:

1. A method of treating a medical condition in a patient having a vagus nerve and a heart that generates a cardiac signal having a QRS wave portion, comprising:

detecting a portion of the QRS wave portion of the patient's cardiac signal;

after detecting the portion of the QRS wave portion, generating a microburst comprising 2 to 20 electrical pulses; and

delivering the microburst to the vagus nerve of the patient.

2. The method of claim 1, further comprising, generating additional electrical pulses after detecting another QRS wave portion of the cardiac signal.

3. The method of claim 1, further comprising, after detecting the portion of the QRS wave portion, waiting a predetermined delay period before generating the microburst.

4. The method of claim 1, further comprising, after detecting the portion of the QRS wave portion, waiting less than about 1000 milliseconds before generating a second microburst comprising from 2 to 20 electrical pulses.

5. The method of claim 1, wherein the electrical pulses of the microburst are generated in a series having a first pulse and a last pulse, each pulse other than the last pulse being separated from a successor pulse in the series by an interpulse interval having a duration, the duration of the interpulse interval increasing along the series from the first pulse to the last pulse.

6. The method of claim 1, wherein the electrical pulses have a pulse width of from about 50 microseconds to about 1000 microseconds, and have a pulse current amplitude of from about 0.25 mA to about 8 mA.

7. The method of claim 1, wherein the electrical pulses of the microburst are generated in a series having a last pulse, each pulse other than the last pulse of the series being separated from a successor pulse in the series by an interpulse interval, each interpulse interval being less than about 40 milliseconds.

8. The method of claim 1, wherein the electrical pulses of the microburst are generated in a series having a last pulse, each pulse other than the last pulse of the series being separated from a successor pulse in the series by an interpulse interval, each interpulse interval having been determined empirically for the patient.

9. The method of claim 1, wherein the electrical pulses of the microburst are generated in a series having a last pulse, each pulse other than the last pulse of the series being separated from a successor pulse in the series by an interpulse interval of about 3 milliseconds to about 10 milliseconds.

10. The method of claim 1, wherein the patient is breathing and has a heart with a heart rate variability, the method further comprising restricting the patient's breathing to increase the heart rate variability.

11. An exogenous electrical signal adapted to be delivered to a vagus nerve of a patient having a brain and a medical condition, the vagus nerve evoking a vagal evoked potential in the brain, the exogenous electrical signal comprising a series of microbursts, each microburst in the series comprising from 2 to 20 electrical pulses, wherein the exogenous electrical signal is adapted to treat the medical condition by enhancing the vagal evoked potential in the brain.

12. An implantable device configured to apply the signal of claim 11.

13. An exogenous electrical signal adapted to be delivered to a vagus nerve of a patient having a brain and a medical condition, the vagus nerve evoking a vagal evoked potential in the brain, the exogenous electrical signal comprising a series of microbursts, each microburst having a duration less than about one second, wherein

the exogenous electrical signal is adapted to treat the medical condition by enhancing the vagal evoked potential in the brain.

14. An implantable device configured to apply the signal of claim 13.

15. An exogenous electrical signal adapted to be delivered to a vagus nerve of a patient having a brain, a medical condition, and a heart operating in a cardiac cycle with an R wave portion, the vagus nerve evoking a vagal evoked potential in the brain, the exogenous electrical signal adapted to treat the medical condition by enhancing the vagal evoked potential in the brain, the signal comprising:

a series of microbursts, each microburst comprising 2 to 20 electrical pulses, and each of the microbursts occurring after a selected R wave portion of the cardiac cycle.

16. The signal of claim 15, wherein each R wave portion is separated from a successive R wave portion by an R-R interval, each R-R interval has a duration and a previous R-R interval preceding it, and each of the microbursts occurs after an R-R interval having a duration that is shorter than the duration of the previous R-R interval.

17. The signal of claim 15, wherein the pulses of the microbursts are spaced to simulate endogenous afferent activity occurring at a particular time in the cardiac cycle.

18. The signal of claim 15, wherein each of the microbursts is delayed relative to the selected R wave portion to simulate endogenous afferent activity occurring at a particular time in the cardiac cycle.

19. The signal of claim 15, wherein each of the microbursts occurs less than about 1000 milliseconds after the selected R wave portion.

20. An exogenous electrical signal adapted to be delivered to a vagus nerve of a patient having a brain, lungs, a medical condition, and a heart with a cardiac signal comprising an inspiration portion corresponding to an inspiration of air by the

lungs and an expiration portion corresponding to an expiration of air by the lungs, the inspiration portion having a series of R wave portions, the expiration portion having a series of R wave portions, the vagus nerve evoking a vagal evoked potential in the brain, the exogenous electrical signal adapted to be delivered to the vagus nerve to treat the condition or disorder of the nervous system by enhancing the vagal evoked potential in the brain, the signal comprising:

a series of microbursts, each microburst in the series comprising from 2 to 20 electrical pulses, each of the microbursts being delivered to the vagus nerve in response to a selected R wave portion of the inspiration portion of the cardiac signal, and none of the microbursts being delivered in response to the R wave portions of the expiration portion of the cardiac signal.

21. The signal of claim 20, wherein the pulses of the microbursts are spaced to simulate endogenous afferent activity occurring at a particular time in the cardiac signal.

22. The signal of claim 20, wherein the pulses of the microbursts are spaced to simulate endogenous afferent activity occurring at a particular time during inspiration of air by the lungs.

23. The signal of claim 20, wherein the microbursts are spaced to simulate endogenous afferent activity occurring at a particular time in the cardiac signal.

24. The signal of claim 20, wherein the microbursts are spaced to simulate endogenous afferent activity occurring at a particular time during inspiration of air by the lungs.

25. A method of customizing an exogenous electrical signal adapted to be delivered to a vagus nerve of a patient having a brain and a medical condition, and to elicit a desired vagal evoked potential in a selected structure of the brain associated with the medical condition, the method comprising:

determining a value of a signal parameter;

generating an electrical signal according to the signal parameter, the electrical signal comprising a series of microbursts, each microburst comprising a series of from 2 to 20 electrical pulses;

delivering the electrical signal to the vagus nerve of the patient;

analyzing an EEG of the patient's brain created during the delivery of the electrical signal to the vagus nerve of the patient to determine the vagal evoked potential observed in the selected structure of the brain; and

modifying the value of the signal parameter based on the vagal evoked potential observed in the selected structure of the brain to modify the vagal evoked potential observed therein.

26. The method of claim 25, 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.

27. The method of claim 25, wherein the signal parameter is a parameter selected from the group consisting of a pulse width, a pulse frequency, an interpulse interval between two of the pulses of the microburst, a frequency of the microbursts, a number of microbursts of the series of microburst, a duration of the electrical signal, a number of pulses in the microbursts, and combinations thereof.

28. The method of claim 25, wherein the patient has a heart that generates a series of QRS waves, each of the microbursts is delivered to the vagus nerve after a selected QRS wave of the series of QRS waves, and the signal parameter comprises a delay period between each microburst and the selected QRS wave.

29. The method of claim 25, wherein the patient has a heart that generates a series of QRS waves, and the signal parameter comprises a selected QRS wave of the series of QRS waves to precede each microburst of the series of microbursts.

30. A method of treating a medical condition in a patient having a vagus nerve and a heart that generates a cardiac signal having a QRS wave portion, comprising:

detecting the QRS wave portion of the cardiac signal;

generating a microburst comprising a series electrical pulses separated by an interpulse interval, the sum of the interpulse intervals separating the pulses being less than 60 milliseconds; and

delivering the microburst to the vagus nerve of the patient.

31. The method of claim 30, further comprising, after detecting the QRS wave portion, waiting a predetermined delay period before applying the microburst to the vagus nerve.

32. The method of claim 30, further comprising, after detecting the QRS wave portion, waiting less than about 500 milliseconds before applying the microburst to the vagus nerve.

33. The method of claim 30, wherein the electrical pulses have a pulse width of from about 50 microseconds to about 1000 microseconds.

34. The method of claim 30, wherein the electrical pulses of the microburst are generated in a series having a last pulse, each pulse other than the last pulse of the series being separated from a successor pulse in the series by an interpulse interval, each interpulse interval being less than about 40 milliseconds.

35. The method of claim 30, wherein each of the interpulse intervals is determined empirically for the patient.

36. The method of claim 30, wherein each of the interpulse intervals is about 3 milliseconds to about 12 milliseconds.

37. The method of claim 30, wherein the patient is breathing and has a heart with a heart rate variability, the method further comprising restricting the patient's breathing to increase the heart rate variability.

38. A system for treating a medical condition in a patient having a vagus nerve and a heart that generates a cardiac signal having a QRS wave portion, the system comprising:

a sensor configured to detect a portion of the QRS wave portion of the cardiac signal;

an electrical signal generator configured to generate a microburst after the detection of the portion of the QRS wave portion by the sensor, the microburst having a duration of less than about one second; and

an electrode in electrical communication with the vagus nerve, the electrode being configured to deliver the microburst to the vagus nerve of the patient.

39. The system of claim 38, wherein the duration of the microburst is less than about 100 milliseconds.

40. The system of claim 38, wherein the electrical signal generator is configured to wait a predetermined delay period after detection of the portion of the QRS wave portion wave before applying the microburst.

41. The system of claim 38, wherein the microburst comprises a series of electrical pulses having a last pulse, each pulse other than the last pulse of the series being separated from a successor pulse in the series by an interpulse interval of about 3 milliseconds to about 10 milliseconds.

42. A computer readable medium having computer executable components for detecting a QRS wave portion of a cardiac cycle;

generating a microburst having 2 to 20 electrical pulses; and

delivering the microburst via an electrode to the vagus nerve of a patient in response to the detection of the QRS wave portion of a cardiac cycle.

43. The computer readable medium of claim 42, wherein the electrical pulses of the microburst are generated in a series having a last pulse, each pulse other than the last pulse being separated from a successor pulse in the series by an interpulse interval having a duration, the computer readable medium further comprising

computer executable components for determining the duration of each of the interpulse intervals.

44. A method of treating a medical condition in a patient having a vagus nerve, comprising allowing the patient to manually trigger generation of an exogenous electrical signal comprising a microburst having a duration of less than about one second; and delivering the exogenous electrical signal to the vagus nerve of the patient.

45. The method of claim 45, wherein the patient has a heart that generates a cardiac signal having a QRS wave portion, the method further comprising, detecting the QRS wave portion of the cardiac signal and delivering the microburst of the exogenous electrical signal to the vagus nerve of the patient in response to detection of the QRS wave portion.

46. The method of claim 45, wherein the patient is performing paced breathing before triggering the exogenous electrical signal.

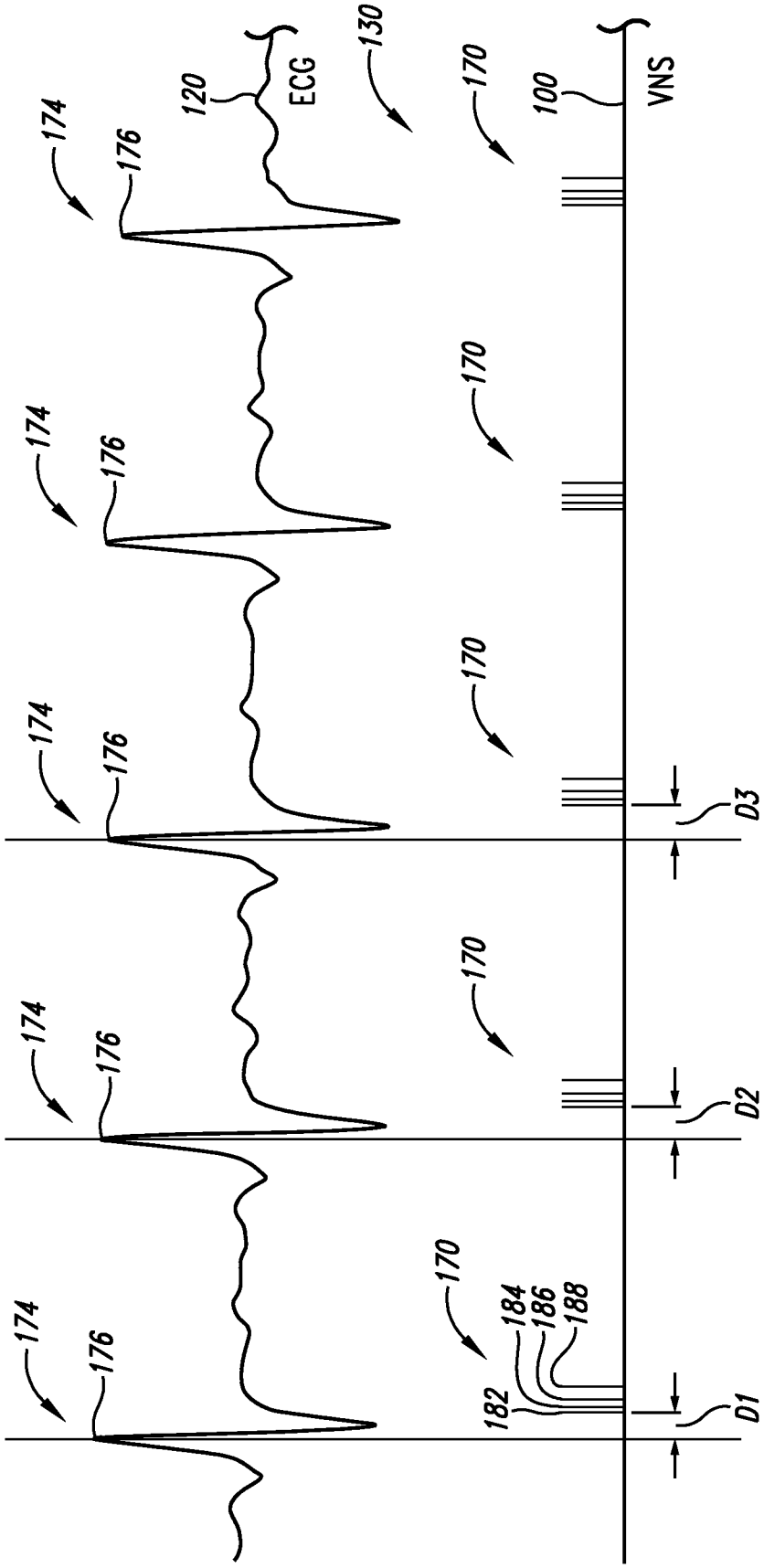


Fig. 1

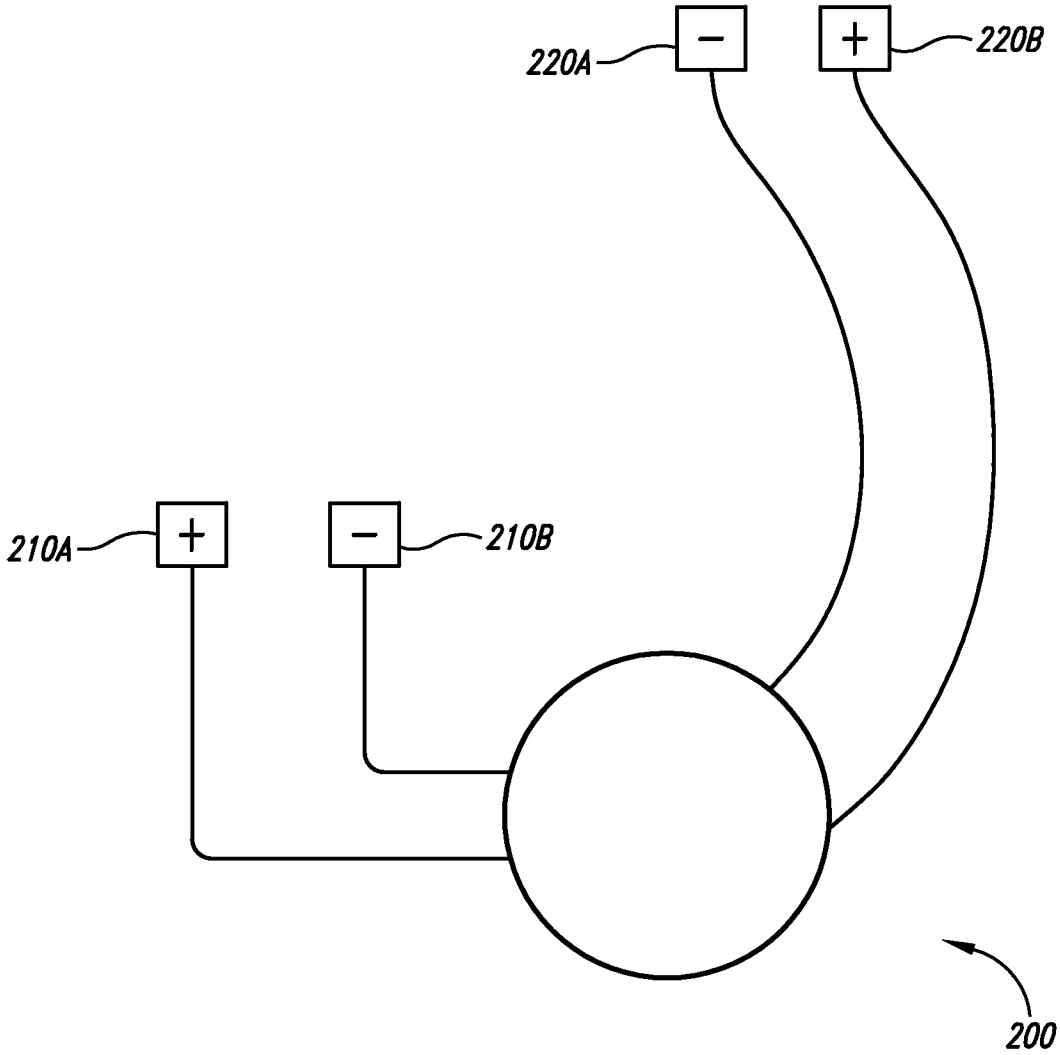
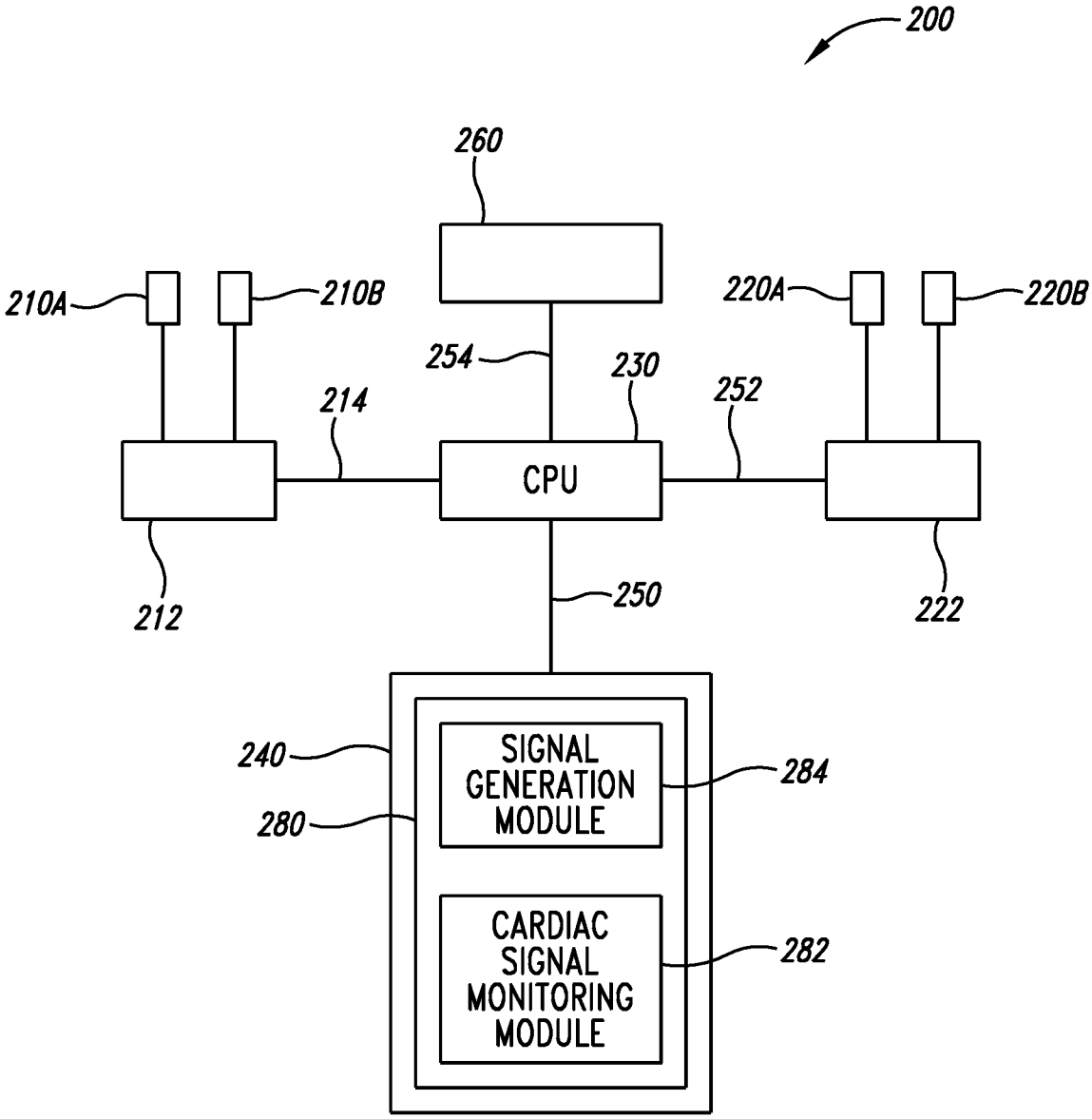


Fig. 2A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260
210A
210B
220A
220B
254
230
252
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CPU
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222
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SIGNAL GENERATION MODULE
284
280
CARDIAC SIGNAL MONITORING MODULE
282

Fig. 2B

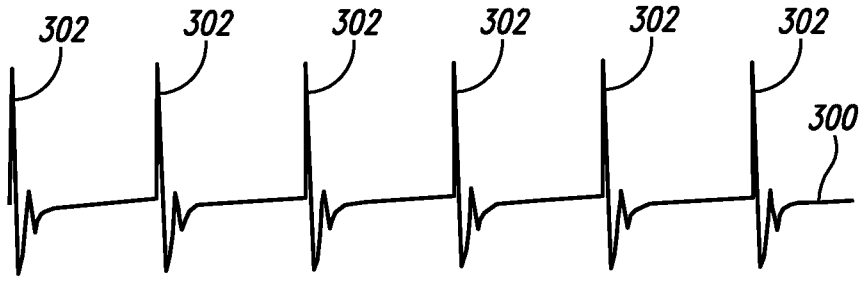


Fig. 3A

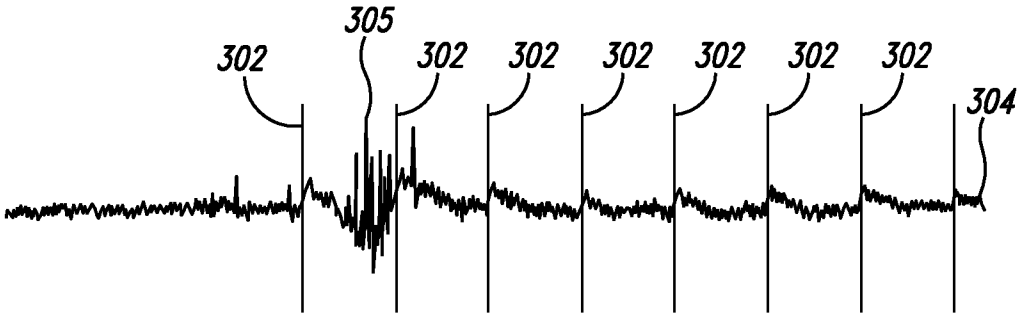


Fig. 3B

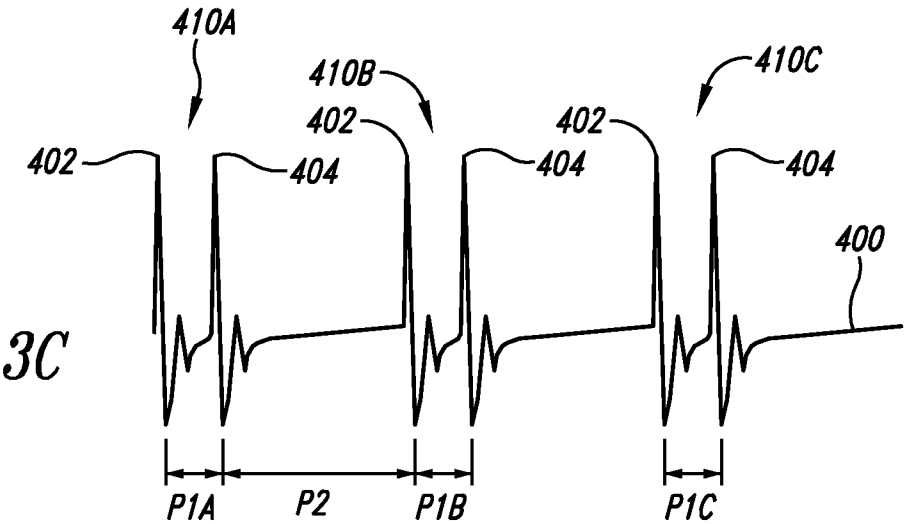
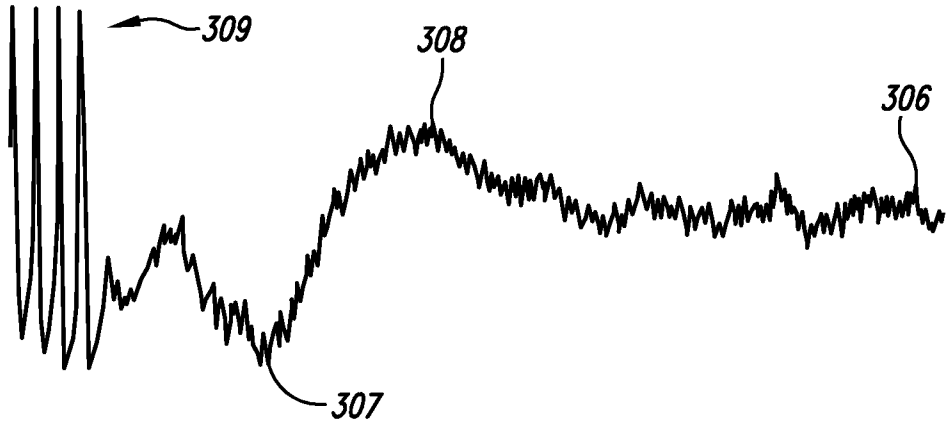


Fig. 3C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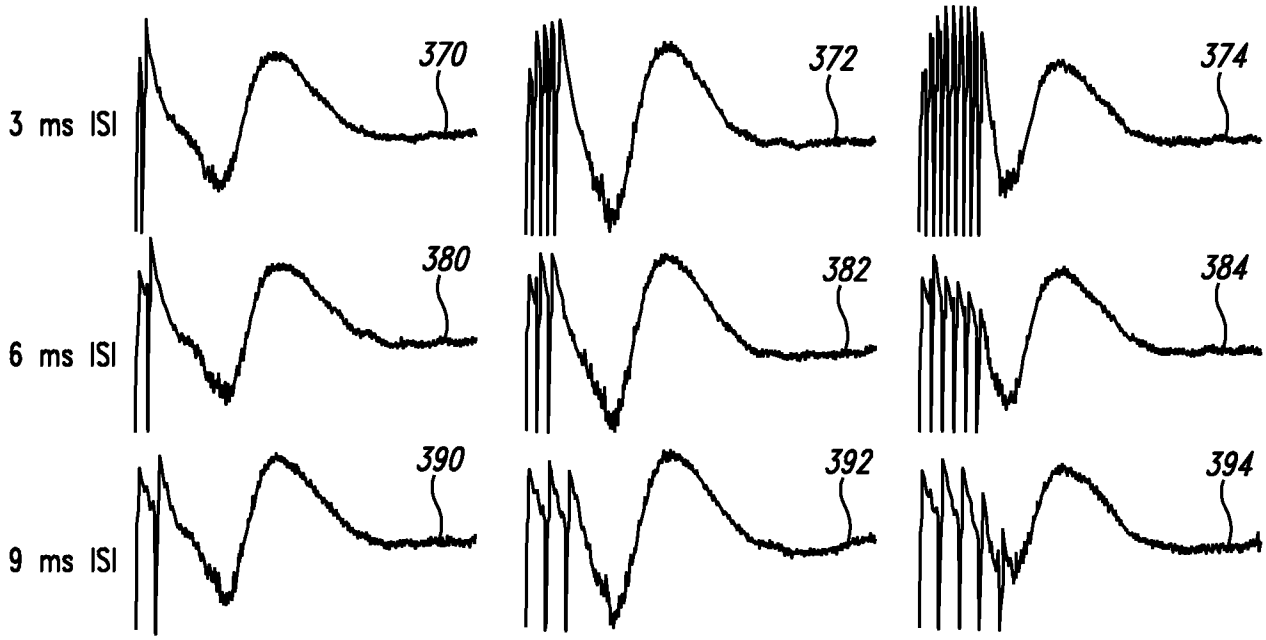
308
306
307

Fig. 3D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382
384
390
392
394

Fig. 3E

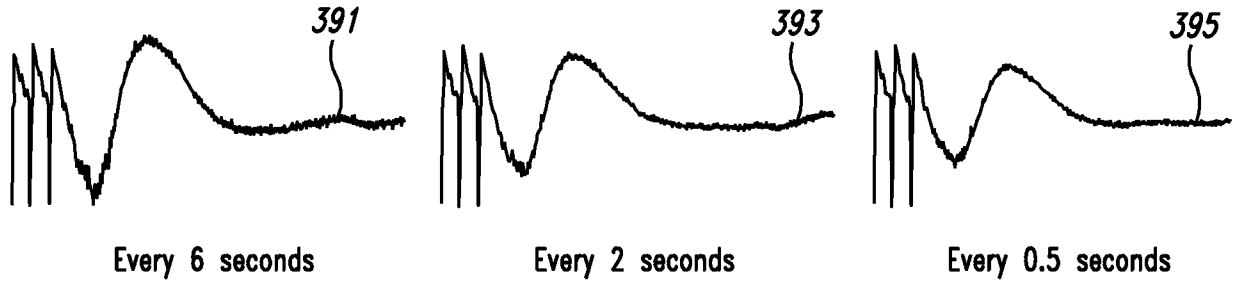
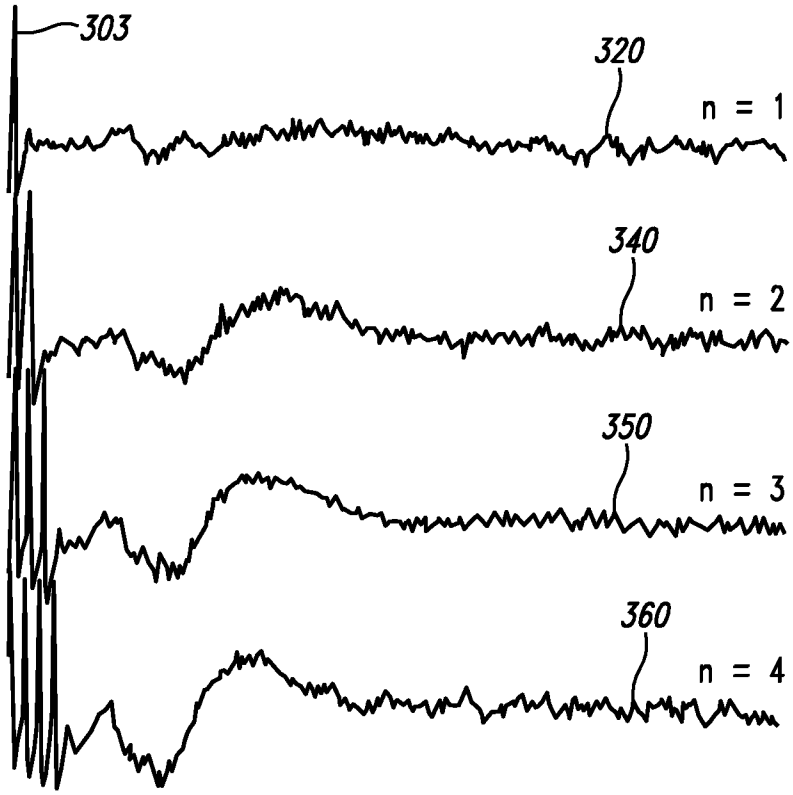

391
393
395
Every 6 seconds
Every 2 seconds
Every 0.5 seconds

Fig. 3F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n = 3
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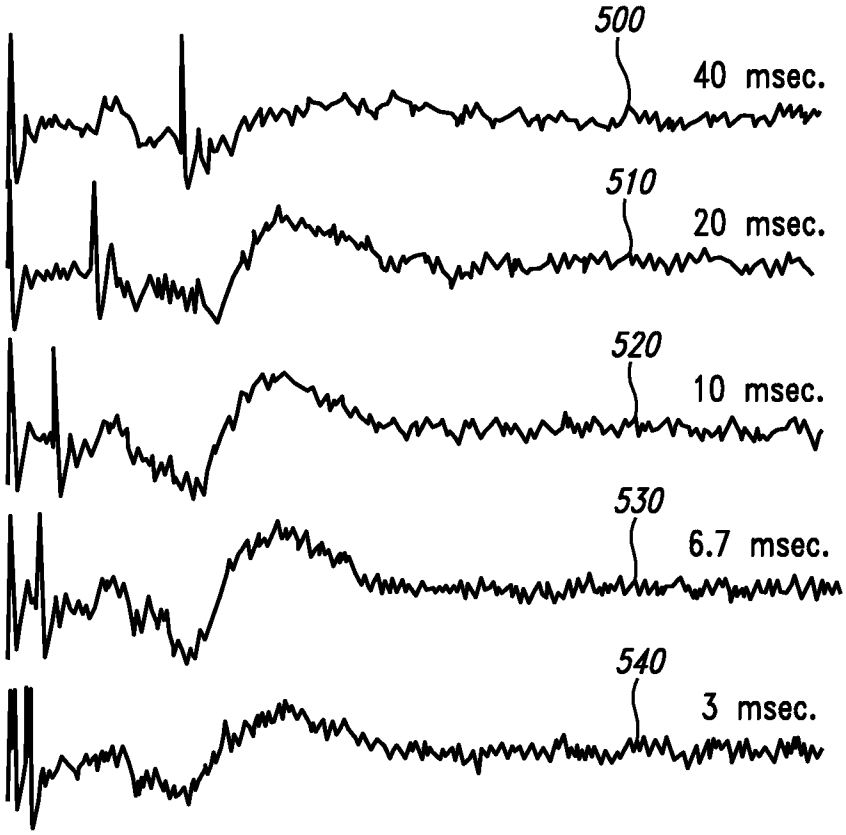
n = 4

Fig. 4A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540
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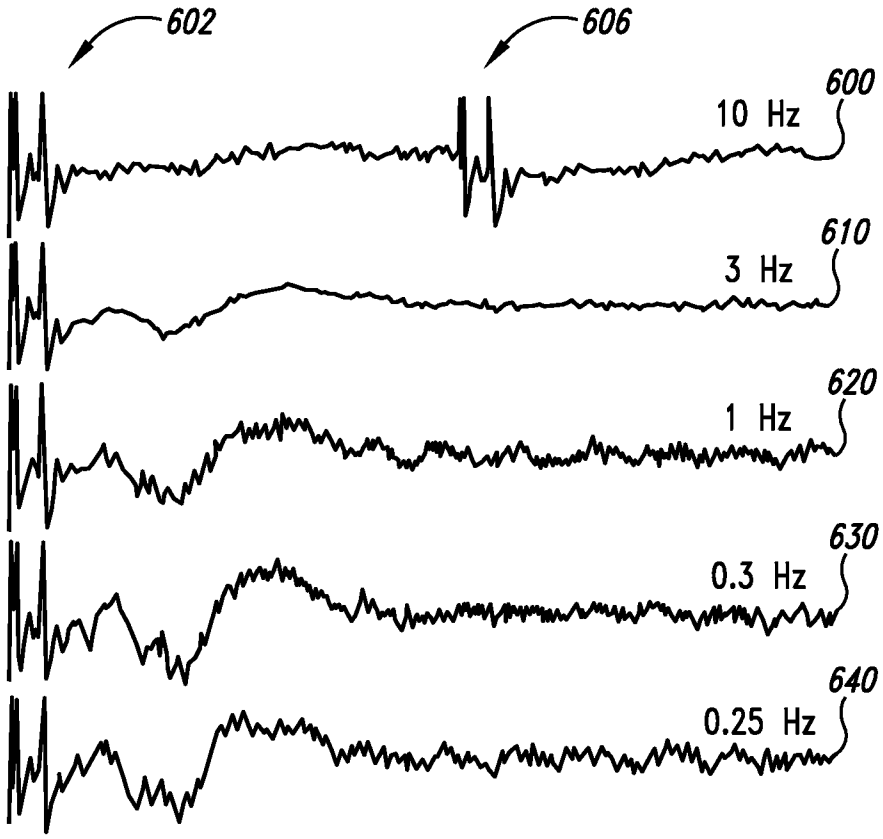
Fig. 4B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606
600
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610
3 Hz
620
1 Hz
630
0.3 Hz
640
0.25 Hz

Fig. 4C

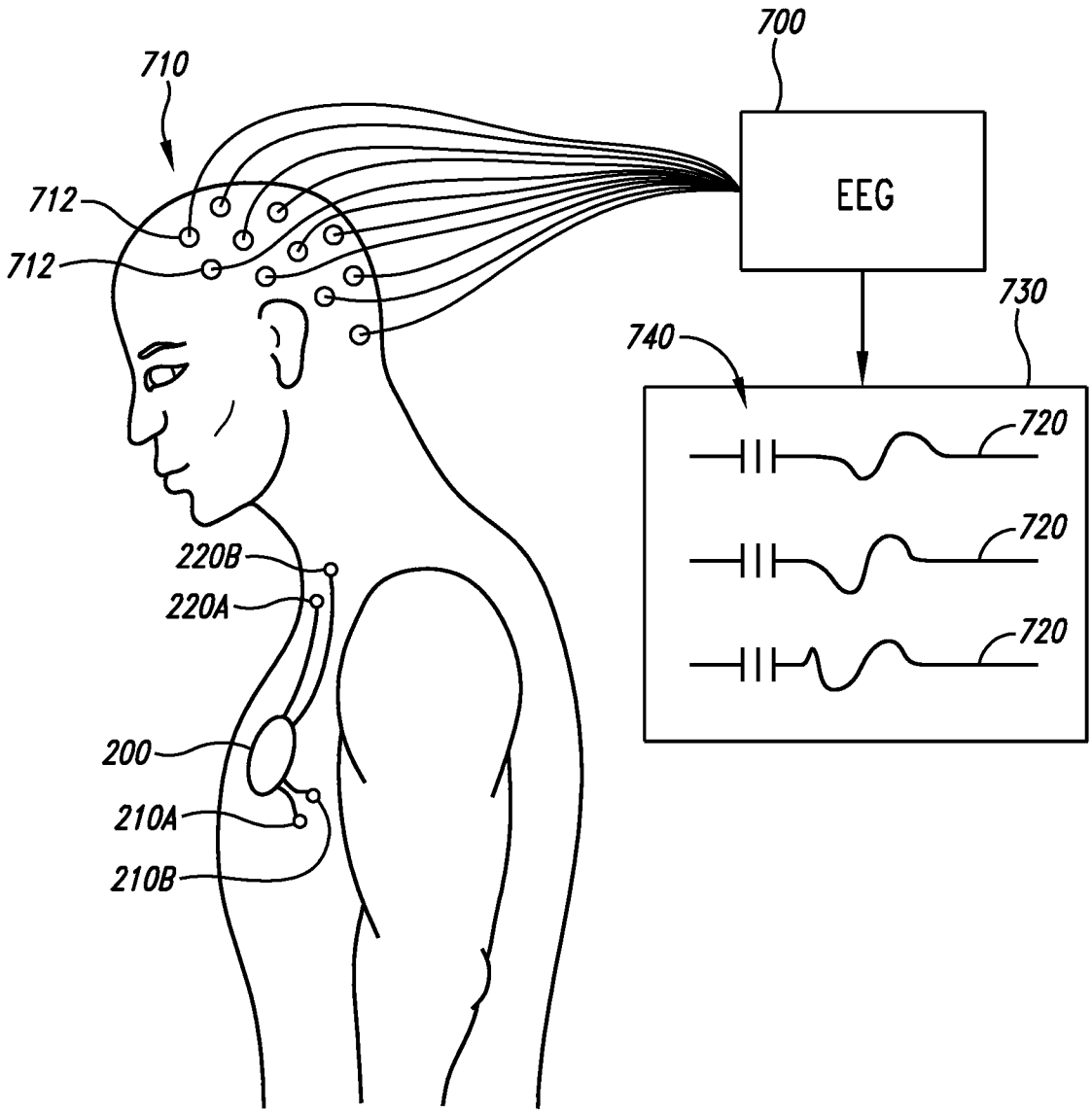

Fig. 5

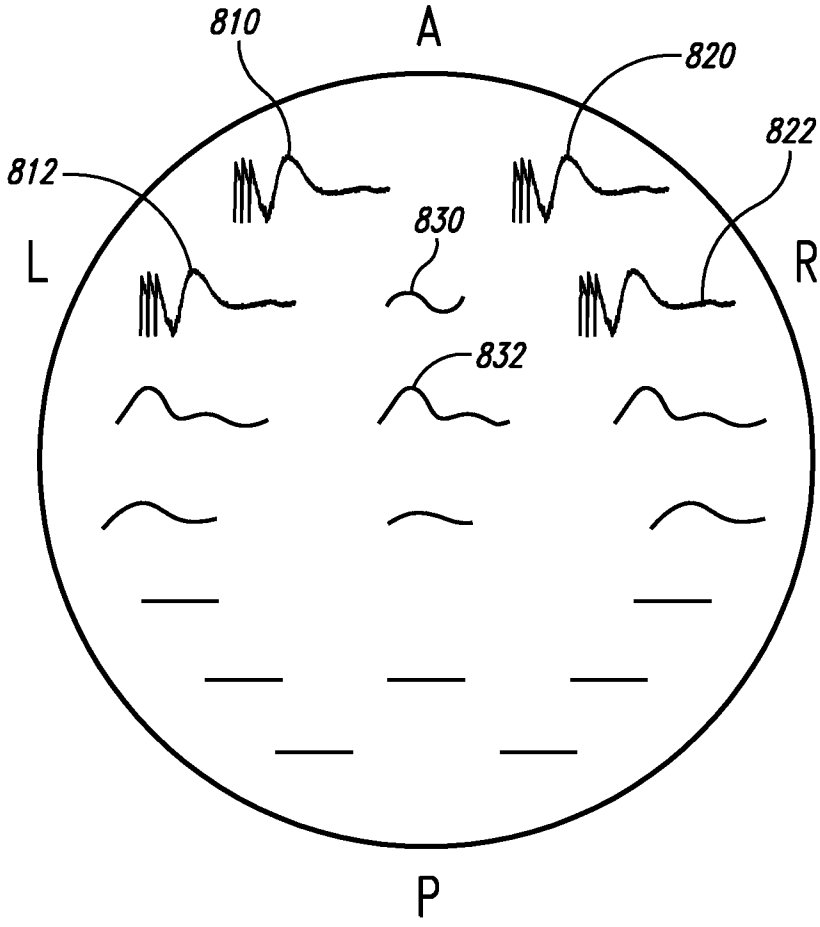

Fig. 6

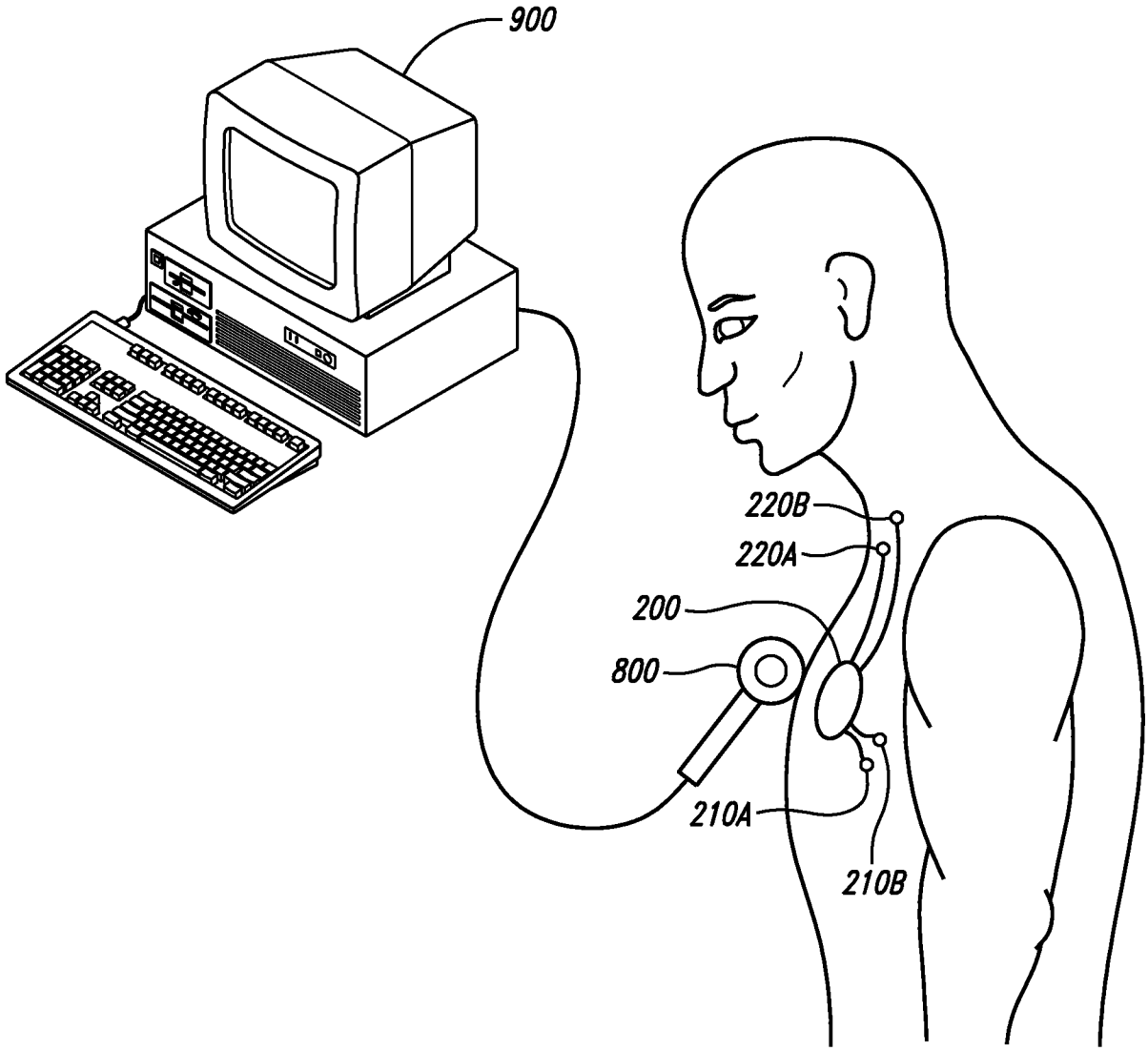

Fig. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2007/065537

A. CLASSIFICATION OF SUBJECT MATTER
INV. A61N1/36

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
A61N A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2005/267542 A1 (DAVID TAMIR B [IL] ET AL) 1 December 2005 (2005-12-01) paragraph [0133] - paragraph [0135]; figures 1,4 paragraph [0650] - paragraph [0652] paragraph [0687] - paragraph [0694] paragraphs [0135], [0174]	38-43
A	EP 1 486 232 A (PACESETTER INC [US]) 15 December 2004 (2004-12-15) paragraph [0074] - paragraph [0082]; figures 5,13	38-43
A	WO 93/21824 A (MEDTRONIC INC [US]) 11 November 1993 (1993-11-11) page 3, line 14 - page 5, line 5; figures 1-3 page 7, line 25 - page 15, line 20	38-43

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 August 2007	31/08/2007

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Scheffler, Arnaud

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2007/065537

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2004/138721 A1 (OSORIO IVAN [US] ET AL) 15 July 2004 (2004-07-15) paragraphs [0011] - [0013], [0033]; figures 2,4	38-43

Form PCT/ISA/210 (continuation of second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2007/065537

Box II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. [X] Claims Nos.: 1-10,25-37,44-46
because they relate to subject matter not required to be searched by this Authority, namely:

Rule 67.1 (iv) PCT - Method for treatment of the human or animal body by therapy (Treating a medical condition by applying electrical signal).

2. [X] Claims Nos.: 11-24
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:

see FURTHER INFORMATION sheet PCT/ISA/210

3. [ ] Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. [ ] As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. [ ] As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. [ ] As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. [ ] No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

[ ] The additional search fees were accompanied by the applicant's protest.

[ ] No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box II.1

Claims Nos.: 1-10,25-37,44-46

Rule 67.1 (iv) PCT - Method for treatment of the human or animal body by therapy (Treating a medical condition by applying electrical signal).

Continuation of Box II.2

Claims Nos.: 11-24

The present claims 11-24 encompass electrical signals defined to fullfil a desired function, contrary to the requirements of clarity of Article 6 PCT, because the result-to-be-achieved type of definition does not allow the scope of the claim to be ascertained, i.e. without providing the technical features necessary for achieving this result. According to Rule 6.3(b) PCT, any dependent claim must contain all the technical features essential to the definition of the invention.

The applicant's attention is drawn to the fact that claims relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure. If the application proceeds into the regional phase before the EPO, the applicant is reminded that a search may be carried out during examination before the EPO (see EPO Guideline C-VI, 8.5), should the problems which led to the Article 17(2) declaration be overcome.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2007/065537

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2005267542 A1	01-12-2005	NONE	
EP 1486232 A	15-12-2004	US 2004199210 A1	07-10-2004
WO 9321824 A	11-11-1993	AU 3433093 A	29-11-1993
		EP 0593689 A1	27-04-1994
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