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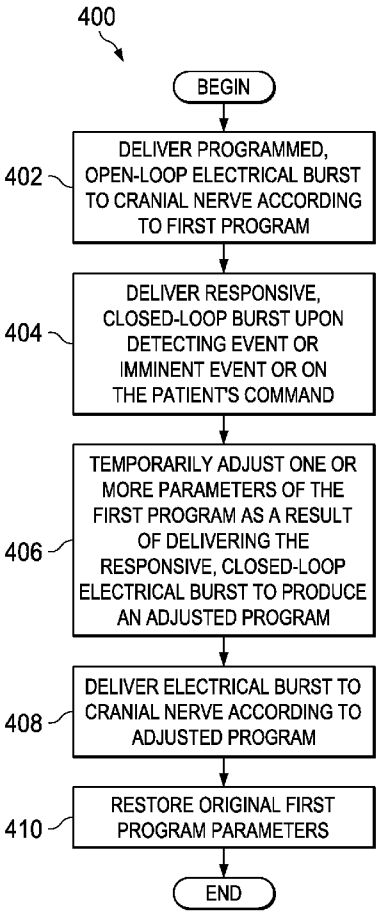

FIG. 4

(57) Abstract: A method comprises applying a first open-loop electrical signal to a neural structure at a first rate. The method also comprises applying a closed-loop electrical signal to the neural structure in response to an event detection, thus causing an overall rate at which electrical stimulation is applied to the neural structure to exceed the first rate. The method further comprises applying a second open-loop electrical signal to a neural structure at a second rate that is lower than the first rate, thus causing the overall rate to be reduced to the first rate.

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DELIVERING SCHEDULED AND UNSCHEDULED THERAPY WITHOUT DETRIMENT TO BATTERY LIFE OR ACCURACY OF LONGEVITY PREDICTIONS

BACKGROUND

[0001] Medical treatments for disorders of the nervous system, such as seizure disorders (e.g., epilepsy), have improved in recent decades. One available treatment involves the application of an electrical signal to reduce various symptoms or effects caused by such neural disorders. For example, electrical signals have been successfully applied at strategic locations in the human body to provide various benefits, including a reduction of seizure occurrence and the improvement of other medical conditions. An example of such a treatment regimen involves the application of electrical stimulation to the vagus nerve of the human body to reduce or eliminate epileptic seizures, as described in U.S. Patent No. 4,702,254, which is incorporated herein by reference.

[0002] Electrical stimulation of a target tissue of a patient's body may be provided by implanting an electrical device (known as an implantable medical device, or IMD) underneath the skin of a patient and electrically stimulating the target tissue. In some cases, electrical stimulation of target tissue (including, but not limited to neural tissue such as the vagus nerve) may be delivered in accordance with a programmed (or predetermined or "planned") schedule. In such cases, the electrical stimulation is referred to as "open-loop," "passive," or "non-feedback" stimulation. In other cases, electrical stimulation may be delivered in response to detecting some type of event. In one embodiment, the event may be patient-initiated. In another embodiment, the event may be detecting a change in one or more body parameters (for example, cardiac rhythm, muscle activity, or body movements). Typically, the parameter(s) is selected such that the change is indicative of a disease state such as an epileptic seizure. This type of stimulation is known as "closed-loop," "active" or "feedback" stimulation. In some devices, both open-loop and closed-loop stimulation may be simultaneously employed, with an open-loop program operating to provide a basic level of therapy and closed-loop stimulation provided in response to episodic events.

[0003] Whether delivered as closed-loop or open-loop, the stimulation is typically applied as a sequence of pulses (collectively referred to as a "burst") extending for a

defined duration (known as the "on-time" or "burst duration"). In open-loop stimulation, the pulse bursts are separated by a programmed time period (the "off-time"), and in closed-loop stimulation the bursts are delivered in response to the detected event and may include a refractory period after the closed-loop burst to allow the nerve to recover. During the on-time of a pulse burst, electrical pulses of a defined electrical current (e.g., 0.5 – 3.5 milliamps) and pulse width (e.g., 0.25 – 1.0 milliseconds) are delivered at a defined frequency (e.g., 20 – 30 Hz) for the burst duration (e.g., 7 - 60 seconds). For open-loop stimulation, the on-time and off-time parameters together define a duty cycle, which is the ratio of the on-time to the combination of the on-time and off-time, and which describes the percentage of time that the electrical signal is applied to the nerve.

[0004] Most IMDs are powered by batteries; consequently, the amount of power available to them is finite. Just before the battery of an IMD is exhausted, the IMD must be surgically removed from a patient's body so that a new device (or battery) may be installed. For this reason, the ability to accurately predict a battery's remaining life is crucial to ensuring that therapy to the patient is not interrupted, which may endanger the patient's health. Overestimating an IMD's battery life can result in interruption of therapy by precluding timely replacement of the IMD and/or battery prior to exhaustion of its electrical charge. One the other hand, underestimating an IMD's battery life can result in surgery that is not necessary at that time and a waste of the useful life of the IMD.

[0005] Predicting battery life generally is relatively uncomplicated when an IMD only applies electrical pulses in accordance with a planned schedule ("open-loop" stimulation). When closed-loop stimulation is used (either alone or in combination with open-loop stimulation), predicting battery life becomes difficult, because closed-loop stimulation is patient-specific and does not occur according to any predetermined schedule. Further, delivering closed-loop stimulation in addition to scheduled, open-loop stimulation may result not only in overstimulation but also may substantially reduce battery life.

[0006] Thus, methods and systems for conserving, extending and accurately predicting battery life in IMDs that apply closed-loop stimulation are desired.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] For a detailed description of exemplary embodiments of the invention, reference will now be made to the accompanying drawings in which:

[0008] Figure 1 shows an illustrative stimulation system coupled to a human cranial nerve, consistent with embodiments of the invention;

[0009] Figure 2 shows a block diagram of the implantable medical device shown in Figure 1, consistent with embodiments of the invention;

[0010] Figures 3a-3m show various patterns of stimulation that the implantable medical device of Figure 2 may provide, consistent with embodiments of the invention;

[0011] Figure 4 shows a flow diagram of an illustrative method usable in conjunction with the system of Figure 1, consistent with embodiments of the invention; and

[0012] Figure 5 shows a flow diagram of another illustrative method usable in conjunction with the system of Figure 1, consistent with embodiments of the invention.

NOTATION AND NOMENCLATURE

[0013] Certain terms are used throughout the following description and claims to refer to particular system components. As one skilled in the art will appreciate, companies may refer to a component by different names. This document does not intend to distinguish between components that differ in name but not function. In the following discussion and in the claims, the terms "including" and "comprising" are used in an open-ended fashion, and thus should be interpreted to mean "including, but not limited to… ." Also, the term "couple" or "couples" is intended to mean either an indirect or direct electrical connection. Thus, if a first device couples to a second device, that connection may be through a direct electrical connection, or through an indirect electrical connection via other devices and connections.

DETAILED DESCRIPTION

[0014] The following discussion is directed to various embodiments of the invention. Although one or more of these embodiments may be preferred, the embodiments disclosed should not be interpreted, or otherwise construed, as limiting the scope of the disclosure, including the claims. In addition, one skilled in the art will understand that the following description has broad application, and the discussion of any embodiment is meant only to be exemplary of that embodiment, and not intended to intimate that the scope of the disclosure, including the claims, is limited to that embodiment.

[0015] Disclosed herein are various techniques for conserving, extending and accurately predicting battery life in an implantable medical device (IMD) that delivers both

open-loop and closed-loop electrical stimulation. Techniques for conserving and extending battery life are described first, followed by a description of techniques for accurately predicting battery life.

[0016] In some battery life conservation embodiments of the present invention, the predetermined schedule at which open-loop stimulation is to be administered is dynamically adjusted to compensate for any closed-loop stimulation burst that is provided outside the predetermined open-loop schedule. For example, in some of these embodiments, a closed-loop stimulation burst may cause the open-loop stimulation schedule to be "reset" so that open-loop stimulation bursts are delivered as scheduled, but with the schedule "resynchronized" to provide subsequent open-loop bursts based upon the closed-loop stimulation burst rather than the immediately preceding open-loop burst. In some embodiments, a closed-loop stimulation burst may cause the next planned open-loop stimulation burst to be skipped, such that the closed-loop burst is "substituted" for the skipped open-loop burst. In some embodiments, a closed-loop stimulation burst may be compensated for by increasing the length of one or more off-time cycles following the closed-loop stimulation burst; similarly, in some embodiments, a closed-loop stimulation burst may be compensated for by decreasing the length of one or more scheduled stimulation bursts following the closed-loop stimulation burst. In some cases, one or more of the foregoing techniques may be combined. Various embodiments are now described in detail with reference to the figures.

[0017] Figure 1 illustrates an implantable medical device (IMD) 110 having a main body 112 comprising a can 121 with a connector 114 for connecting to leads 122. The IMD 110 is implanted in a patient's chest in a pocket or cavity formed by the implanting surgeon just below the skin, similar to the implantation procedure for a pacemaker pulse generator. A stimulating nerve electrode assembly 125, preferably comprising an electrode pair, conductively couples to the distal end of an insulated and electrically conductive lead assembly 122, which preferably comprises a pair of lead wires (one wire for each electrode of an electrode pair). Lead assembly 122 is attached at its proximal end to the connector 114 on can 121. The electrode assembly is surgically coupled to a cranial nerve, such as a vagus nerve 127 in the patient's neck. The electrode assembly 125 preferably comprises a bipolar stimulating electrode pair, such as the electrode pair

described in U.S. Patent No. 4,573,481, which is incorporated herein by reference. Persons of skill in the art will appreciate that many electrode designs could be used in the present disclosure. The two electrodes are preferably wrapped around the vagus nerve, and the electrode assembly 125 preferably is secured to the nerve 127 by a spiral anchoring tether such as that disclosed in U.S. Patent No. 4,979,511, which is incorporated herein by reference. Lead assembly 122 may be secured, while retaining the ability to flex with movement of the chest and neck, by a suture connection to nearby tissue.

[0018] The IMD 110 may be controlled or programmed with an external device 150 (e.g., a computer) and a programming wand 155 to facilitate radio frequency (RF) communication between the external device 150 and the IMD 110. The wand 155 and software permit noninvasive communication with the IMD 110 after the latter is implanted. In systems where the external device 150 uses one or more channels in the Medical Implant Communications Service (MICS) bandwidths, the programming wand 155 may be omitted to permit more convenient communication directly between the external device 150 and the IMD 110.

[0019] Figure 2 illustrates a block diagram of IMD 110 for performing neurostimulation in accordance with embodiments of the present disclosure. In one embodiment, the IMD 110 comprises a power source 210, a power-source controller 220, a stimulation controller 230, a power regulation unit 240, a stimulation unit 250, a communication unit 260 and storage 280. The stimulation controller 230 and stimulation unit 250 together form stimulation logic 255. Storage 280 may be used for storing various program codes, starting data, and the like. The power source 210 may comprise a battery, which may be rechargeable or non-rechargeable. Other power sources, such as capacitors, may also be used. The power source 210 provides power for the operation of the IMD 110, including electronic operations and stimulation bursts. Power source 210, in one embodiment, may be a lithium-thionyl chloride cell or a lithium/carbon monofluoride (LiCFx) cell. The terminals of the power source 210 preferably electrically couple to an input side of the power-source controller 220 and the power regulation unit 240.

[0020] The power-source controller 220 preferably comprises circuitry for controlling and monitoring the flow of electrical power to various electronic and stimulation-delivery

portions of the IMD 110 (such as the components 230, 240, 250, 260 and 280 illustrated in Figure 2). More particularly, the power-source controller 220 is capable of monitoring the power consumption or charge depletion of the IMD 110, measuring the voltage across the power source 210, and generating elective replacement and/or end-of-service signals.

[0021] The communication unit 260 facilitates communication between the IMD 110 and the external unit 150, as shown. The external unit 150 may be a device that is capable of programming various components and stimulation parameters of the IMD 110. In one embodiment, the external unit 150 is a computer system capable of electronic communications, programming, and executing a data-acquisition program, preferably a handheld computer or PDA. The external unit 150 preferably is controlled by a healthcare provider such as a physician in, for example, a doctor's office. The external unit 150 may be used to download various parameters and program software into the IMD 110 for programming the operation of the IMD. The external unit 150 may also receive and upload various status conditions and other data from the IMD 110. The communication unit 260 may comprise hardware, software, firmware or any combination thereof. Communications between the external unit 150 and the communication unit 260 may occur via a wireless or other type of communication, illustrated generally by line 275 in Figure 2.

[0022] The power regulation unit 240 is capable of regulating power delivered by the power source 210 to particular components of the IMD 110 according to their needs and functions. The power regulation unit 240 may perform a voltage conversion to provide appropriate voltages and/or currents for the operation of the components. The power regulation unit 240 may comprise hardware, software, firmware or any combination thereof. The communication unit 260 is capable of providing transmission and reception of electronic signals to and from an external unit 150.

[0023] Stimulation controller 230 defines the electrical stimulation pulses to be delivered as part of a burst to the nerve tissue according to parameters and waveforms that may be programmed into the IMD 110 using the external unit 150 or that may be pre-programmed into the controller 230 prior to or after implantation of the IMD 110 into the patient's body. The stimulation controller 230 controls the operation of the stimulation unit 250, which generates the stimulation pulses comprising a burst according to the parameters defined

by the controller 230 and, in some embodiments, provides these pulses to the lead assembly 122 and electrode assembly 125. Stimulation pulses provided by the IMD 110 may vary widely across a range of parameters. The stimulation controller 230 may comprise hardware, software, firmware or any combination thereof.

[0024] In some embodiments, the stimulation logic 255 (stimulation controller 230 and stimulation unit 250) delivers stimulation bursts in response to certain events. For example, in some cases, the controller 230 and the unit 250 may deliver a stimulation burst in response to detecting an impending or already-occurring seizure based on one or more of the patient's cardiac parameters (e.g., heart rate, rate of change of heart rate, heart rate variability, etc.). However, detection logic 270 may be implemented anywhere on the patient's body to detect any type of event. In some embodiments, the detection logic 270 may be disposed in a location other than the patient's body to detect some other type of event independent of the patient's body (e.g., a request for a stimulation burst initiated by the patient). Detection logic 270 may include a sensor (e.g., a sensor that detects user input, such as a tap or magnetic input apparatus). Upon detecting an event, the detection logic 270 causes the stimulation controller 230 to activate the stimulation unit 250 in response to the detected event. One or more of the blocks 210-280 may comprise hardware, firmware, software or any combination thereof.

[0025] Figures 3a-3m show waveforms that represent various ways in which the stimulation controller 230 may cause the stimulation unit 250 to deliver stimulation pulse bursts to the nerve to which the IMD 110 couples. In each of the waveforms of Figures 3a-3m, the x-axis represents time and the y-axis represents electrical stimulation strength (e.g., current). The scope of this disclosure is not limited to the stimulation depicted in Figures 3a-3m.

[0026] Figure 3a shows a waveform that represents an example of programmed, open-loop stimulation pulse bursts. As shown, during typical, open-loop stimulation with no closed-loop stimulation interruptions, pulse bursts are delivered at regular intervals according to programmed parameters defining the duration of the bursts (i.e., on-time), the current, frequency and pulse width of each pulse within the burst, and the time between each burst (i.e., off-time). In the embodiment depicted in Figure 3a, each burst lasts for 2 seconds and each programmed off time lasts for 13 seconds. An entire on-

time / off-time cycle thus lasts for 15 seconds, with the pulses comprising the burst defined by one or more programmed parameters such as current, pulse width and frequency. The timing can be varied as desired by programming different values for the on-time and the off-time. In such embodiments, electrical stimulation dosing, battery usage and battery life are predictable because all stimulation bursts are delivered according to the programmed parameters in advance of delivery.

[0027] Figure 3b shows a waveform that represents a scheduled, open-loop stimulation burst pattern to which a responsive, closed-loop stimulation burst has been added. Bursts 310, 312, 314, 316, 317 and 318 are scheduled, open-loop stimulation bursts. In contrast, burst 319 is an unscheduled, closed-loop stimulation burst. Stimulation unit 250 delivers the burst 319 as a result of some event, such as, for example, the detection of a particular cardiac change that signals an ongoing or impending seizure. In some embodiments, the burst 319 may be delivered as the result of manual instruction (e.g., the patient waves a magnet near the IMD 110, thereby triggering delivery of the burst 319). However, as shown, despite delivery of the burst 319, the open-loop stimulation bursts are delivered as programmed, just as they were delivered as shown in Figure 3a. In the scheme shown in Figure 3b, stimulation dosing, battery usage and battery life all are unpredictable, or poorly predictable. However, therapy for the patient may be improved because closed-loop stimulation bursts are delivered as needed in response to, for example, an acute episodic event such as an epileptic seizure.

[0028] Figure 3c shows an embodiment of the present invention in which a waveform that represents a programmed, open-loop stimulation burst pattern has been modified as the result of introducing an unprogrammed, closed-loop stimulation burst. Electrical stimulation bursts 320, 322, 324, 326 and 328 are programmed, open-loop bursts. Burst 329 is a responsive, closed-loop burst. Burst 320 is delivered at time t=0 and lasts for 2 seconds, until t=2. After t=2, 13 seconds were scheduled to elapse prior to delivery of the next scheduled, open-loop burst – burst 322 (i.e., at t=15). However, instead of the burst 322 being delivered at t=15 seconds, a responsive, closed-loop burst 329 is delivered after an off cycle of only 8.25 seconds (i.e., at t=10.25). This closed-loop burst 329 is delivered on-demand, in response to some event (e.g., detecting an impending seizure, manual stimulation, etc.).

[0029] In the embodiment of Figure 3c, after delivering this unprogrammed, closed-loop burst 329, the IMD 110 reschedules the delivery of the subsequent open-loop bursts 322, 324, 326 and 328, to synchronize them with the responsive, closed-loop burst 329. Specifically, while the open-loop burst 322 was scheduled to be delivered 13 seconds after the end of open-loop burst 320, burst 322 is offset so that it is instead delivered 13 seconds after the end of closed-loop burst 329. Subsequent programmed, open-loop bursts are then delivered after the off-time period following rescheduled burst 322. Thus, while open-loop burst 324 was originally scheduled to be delivered 28 seconds after the end of the programmed, open-loop burst 320, burst 324 is instead delivered 28 seconds after the end of closed-loop burst 329 (i.e., 13 seconds after the end of the rescheduled burst 322). Bursts 326 and 328 are similarly synchronized to be applied 13 seconds after the previous (rescheduled) burst. In the embodiment of Figure 3c, therefore, all subsequent open-loop bursts following an unprogrammed, closed-loop burst are resynchronized to occur at the programmed off-time intervals following the closed-loop burst, rather than occurring the programmed off-time intervals following the open-loop burst that immediately precedes the closed-loop burst. The technique depicted in Figure 3c allows for delivery of responsive, closed-loop therapy bursts while preventing subsequent scheduled, open-loop therapy bursts from being administered unnecessarily early. The embodiment of Fig. 3c will impose an increased battery life cost on the IMD by the sum of the times that each responsive, closed-loop stimulation burst is delivered before the next scheduled, open-loop burst. This time interval may be referred to as “early intervention time” or EIT.

[0030] Figure 3d shows a waveform that represents another scheduled, open-loop stimulation burst pattern that has been modified as the result of introducing an unprogrammed, closed-loop stimulation burst. Electrical stimulation bursts 330, 332, 334, 336, 337 and 338 are programmed, open-loop bursts. Burst 339 is a responsive, closed-loop burst. Burst 330 is delivered at time t=0 and lasts for 2 seconds, until t=2. After t=2, 13 seconds were scheduled to elapse prior to delivery of the next programmed, open-loop burst 332 (i.e., at t=15). Similarly, open-loop burst 334 was scheduled for delivery 13 seconds after the end of burst 332, and so on. However, instead of the burst 332 being delivered at t=15 seconds, an unscheduled, closed-loop burst 339 is delivered in

response to an event. As a result of the delivery of this burst 339, scheduling for the open-loop bursts is adjusted. In particular, as a result of delivering the responsive, closed-loop burst 339 prior to programmed burst 332, the IMD 110 skips delivery of burst 332 so that the programmed, open-loop burst 334 is the next burst to be delivered after the closed-loop burst 339. Moreover, in the embodiment of Figure 3d, burst 334 is delivered at its programmed time, and is unaffected in terms of its timing, by the delivery of closed-loop burst 339. In this way, the total electrical stimulation dosage delivered to the patient remains unchanged from the completely open-loop dosage, despite the periodic occurrence of responsive, closed-loop bursts. In addition to ensuring that the patient is not overdosed, this technique increases predictability of battery life determinations while providing the benefits of on-demand, closed-loop therapy. By considering the responsive, closed-loop burst 339 as a substitute for the next scheduled open-loop burst 332, the embodiment of Fig. 3d will provide improved battery life over the embodiment of Figure 3c, because it does not involve the accumulation of EIT. If the burst parameters defining the closed-loop burst 339 are identical to those of the open-loop burst 332 for which it is substituted, the embodiment of Fig. 3d will provide battery life essentially identical to that of purely open-loop stimulation as depicted in Fig. 3a.

[0031] Figures 3e-3g show other techniques in accordance with various embodiments. Figure 3e illustrates a waveform of another scheduled, open-loop stimulation burst pattern. Specifically, Figure 3e depicts scheduled, open-loop bursts 340, 342, 344, 346 and 348. Each pulse lasts for 2 seconds and is followed by an off-time that lasts for 13 seconds. Thus, pulse 340 begins at t=0 and lasts until t=2, at which time an off-time begins and lasts until t=15. At t=15, pulse 342 begins, and so forth.

[0032] Figures 3f and 3g illustrate alternative approaches to the “resynchronization” approach of Figure 3c and the “substitution” approach of Fig. 3d. More particularly, the approaches outlined in Figs. 3f and 3g permit “recovery” of the time period by which a closed-loop burst is delivered before the next scheduled, open-loop burst. In other words, the Figs. 3f and 3g depict recovery of the early intervention time (EIT) associated with closed-loop stimulation bursts. Figure 3f depicts the introduction of an unprogrammed, closed-loop burst 350 (e.g., in response to detection of an event or impending event). Specifically, at t=10, a responsive, closed-loop burst 344 is delivered as a result of the

IMD 110 detecting an event. Thus, the IMD 110 delivers a responsive burst (i.e., burst 350) 5 seconds before the IMD 110 is scheduled to deliver a burst (i.e., programmed burst 342, as shown in Figure 3e). To maintain consistent total dosage over time, these 5 seconds of EIT may be added back into the schedule by interspersing them among one or more off cycles between programmed, open-loop bursts.

[0033] Figure 3f shows one example of such interspersion. As shown in Figure 3f, in some embodiments, after the responsive burst 350, the next programmed burst 342 may be resynchronized to begin after the programmed off-time has elapsed following the responsive burst 350, as in Figure 3c. After resynchronizing the programmed bursts following the responsive burst 350, the EIT (i.e., the duration of time prior to the scheduled open-loop burst that the responsive, closed-loop burst was delivered) may be recovered by adding all 5 seconds of the EIT back into the open-loop stimulation burst schedule immediately after the first open-loop burst 342 is administered after the programmed off-time following the closed-loop burst 350 (instead of its delivery as originally scheduled after the programmed off-time following the immediately preceding open-loop burst 340). Thus, while open-loop burst 342 was originally scheduled to be delivered at t=15 (as shown in Figure 3e), insertion of the closed-loop burst 350 and the 13-second off cycle associated therewith causes the open-loop burst 342 to be delivered at t=25. Thereafter, the off-time following the open-loop burst 342 is increased by 5 seconds (from 13 seconds to a total of 18 seconds) to allow for recovery of the 5 seconds of EIT associated with delivery of the closed-loop burst 350. Thus, instead of being delivered at t=40 (as would have been the case had the 5 seconds of EIT not been added to the off-time following burst 342), the open-loop burst 344 is delivered at t=45, as originally programmed and scheduled, as illustrated in Figure 3e. As a result of this technique, the total number of bursts (i.e., 5 bursts) delivered over the extended period of time shown in Figures 3e-3f remains the same regardless of whether the responsive, closed-loop burst 344 is delivered or not. Stated another way, although the burst 350 was unscheduled, the technique of recovering the EIT associated with a responsive stimulation burst places the schedule “back on track” to the programmed open-loop schedule by t=45 (compare the timing of bursts 346 and 348 in Figure 3e to the timing of bursts 344 and 346 in Figure 3f, respectively). The total number of bursts delivered

between t=0 and t=45 remains the same, regardless of whether the closed-loop burst 350 is delivered or not (compare the first 4 bursts in Figure 3e with the first 4 bursts in Figure 3f). In some embodiments, the 5 seconds of EIT may be added to the off-time between bursts 350 and 342 or any other pair of bursts.

[0034] In Figure 3f, the entire EIT of 5 seconds is added as a "lump sum" into the single off-time period following open-loop burst 342. In some embodiments, however, the EIT of 5 seconds may be distributed in smaller quantities over a greater number of off-time cycles. Generally, in such embodiments, 5/*n* seconds of the EIT are added to each of *n* off-time cycles. Thus, 5/2 seconds are added to each of 2 off-time cycles; 5/3 seconds are added to each of 3 off-time cycles, and so forth, until the entire EIT period associated with a particular closed-loop burst has been recovered, and the total number of bursts provided is the same as would have been the case had the closed-loop burst not been applied, and only the programmed, open-loop bursts provided. This technique may be generalized by stating that, in such embodiments, *x/n* seconds are added to each of *n* off-time cycles, where *x* represents the early intervention time (EIT). This expression assumes an even distribution of EIT over multiple off-time cycles but, in some embodiments, such distribution of EIT over off-time cycles may be adjusted so that it is uneven (e.g., of a total of 5 seconds EIT, 3 seconds may be added to one off cycle, while 2 seconds are added to another off cycle). It will be appreciated in view of the foregoing disclosure that various mathematical sequences (e.g., linearly increasing, exponentially increasing, random, etc.) may be employed to recover the EIT over a desired number of off-time cycles.

[0035] Figure 3g depicts at least one such embodiment in which 5/2 seconds are added to each of 2 off cycles. The technique shown in Figure 3g is similar to that shown in Figure 3f, with one difference. In Figure 3f, the 5 second EIT is added to the off-time following open-loop burst 342. In contrast, Figure 3g shows the 5 second EIT being distributed across the next two (2) off-time cycles, i.e., the off-times periods following open-loop bursts 342 and 344. Because the 5 second delay is distributed across 2 off-time cycles instead of just 1 off-time cycle, 5/2 seconds are added to each of the off-time cycles. Thus, as shown, 2.5 seconds are added to the off-time following burst 342 and another 2.5 seconds are added to the off-time following burst 344. The technique of

Figure 3f gets the burst deliveries "back on schedule" faster than does the technique of Figure 3g. For instance, Figure 3f shows the 4th burst in the series being delivered at the same time (t=45) as the 4th burst in the series of Figure 3e. In contrast, the technique of Figure 3g does not get the burst deliveries "back on schedule" until t=60, when the 5th burst in the series is delivered at the same time as is the 5th burst in the series of Figure 3e. It should be noted that instead of distributing the 2.5 second EIT installments among the off-times between bursts 342 and 346, as shown in Figure 3g, the 2.5 second installments may be distributed among the off-times between bursts 350 and 344 or among off-times between any number of bursts following closed-loop burst 350.

[0036] Figures 3h-3i depict another technique of compensating for reduced battery life associated with application of a responsive, closed-loop burst in accordance with various embodiments of the present invention. More particularly, in this technique, open-loop bursts that follow a closed-loop burst are shortened to compensate for the extra dosing (i.e., additional electrical charge applied to the target tissue) introduced by the closed-loop burst. This contrasts with the technique of "recovery of EIT" illustrated in Figures 3f and 3g by focusing on recovery of the extra electrical charge (as represented by individual pulses within a pulse burst) applied to the nerve in the responsive, closed-loop burst.

[0037] More generally, the embodiment of Figure 3i (and Figure 3k, discussed hereafter, and other similar but non-illustrated embodiments) adjust a programmed, open-loop electrical signal to compensate for the occurrence of a responsive, closed-loop burst by reducing the amount of charge delivered to the nerve in one or more open-loop bursts following the closed-loop burst, until the total amount of charge delivered in the closed-loop burst has been completely "recovered" from the following closed-loop bursts. This concept of recovering closed-loop charge (CLC) is similar to that of the recovery of EIT discussed earlier (which is a specific embodiment of the more general concept of CLC recovery). In other words, the scheduled delivery of charge in a programmed, open-loop signal is reduced such that the charge delivered in a responsive, closed-loop burst merely substitutes for charge that would otherwise have been delivered as part of the programmed, open-loop signal. In this manner, closed-loop bursts do not increase the amount of charge applied to the nerve (and thus removed from the battery of the IMD) beyond that already programmed to occur under the programmed, open-loop signal.

Instead, the delivery of a closed-loop burst simply alters the timing of the delivery of charge to the nerve, not its rate over longer time periods.

[0038] Figure 3h shows a dosing pattern including only programmed, open-loop pulse bursts. Specifically, Figure 3h depicts scheduled, open-loop bursts 360, 362, 364, 366, 368 and 370. Each burst lasts for 2 seconds and is followed by an off-time that lasts for 13 seconds. Thus, burst 360 begins at t=0 and lasts until t=2, at which time an off-time begins and lasts until t=15. At t=15, pulse 362 begins, and so forth.

[0039] Figure 3i is similar to the pattern of Figure 3h but includes a responsive, closed-loop burst 382. The closed-loop charge (CLC) introduced by the closed-loop burst 382 is compensated for by reducing the electrical charge delivered to the target tissue during one or more subsequent open-loop bursts. For example, as shown, each of the open-loop bursts 384, 386 and 388 is reduced in duration from 2 seconds to 4/3 seconds (i.e., in each of the subsequent bursts, the programmed on-time of 2 seconds is reduced by 2/3 seconds). By reducing the duration of each of three open-loop pulses by one-third of the programmed on-time, a portion of the CLC associated with closed-loop burst 382 is mitigated. Such CLC recovery may be performed in a variety of ways (e.g., by reducing the durations of any suitable number of bursts by any appropriate amount, which may involve performing reductions on any of a variety of bursts (including closed-loop and open-loop bursts), etc.).

[0040] Figure 3k depicts another technique of compensating for reduced battery life associated with application of a responsive, closed-loop burst in accordance with various embodiments of the present invention. In this technique, the duration of an off-time that precedes a burst dictates the duration of that burst. By adjusting burst (i.e., on-time) duration in accordance with the off-time duration preceding it, desired duty cycles (defined as the ratio of on-time to the sum of on-time and off-time) are maintained despite the introduction of responsive, closed-loop bursts.

[0041] Figure 3j shows a dosing pattern including only scheduled, open-loop bursts. Specifically, Figure 3j depicts scheduled, open-loop bursts 400, 402, 404 and 406. Each burst lasts for 4 seconds and is preceded by an off-time that lasts for 16 seconds. Thus, an off-time begins at t=0 and lasts until t=16, at which time an open-loop burst 400 begins and lasts until t=20. At t=20, the next off-time begins, and so forth. By alternating 4

second on-times with 16 second off-times, an on-time to off-time ratio of 1:4 is achieved and maintained.

[0042] Figure 3k shows a pattern similar to that of Figure 3j except it includes a responsive, closed-loop burst 412. To allow for recovery of the CLC delivered by closed-loop burst 412, the next scheduled, open-loop burst 414 is generated at its scheduled time, but the duration (i.e., on-time) of burst 414 is adjusted to be in proportion with the duration of the off-time between the closed-loop burst 412 and the open-loop burst 414. In this example, the off-time between bursts 412 and 414 is 4.8 seconds, and the desired on-time to off-time ratio is 1:4. Thus, the pulse 414 is adjusted to be only 1.2 seconds in duration, since 1.2/4.8 = 1/4. The next open-loop pulse 416 is delivered on schedule and is of the programmed duration. In the example of Figure 3k, only the durations of open-loop bursts are adjusted. The durations of closed-loop pulses are not scaled to meet any particular on-to-off-time ratio.

[0043] In the example of Figure 3m, durations of both closed-loop and open-loop bursts are adjusted to compensate for reduced battery life associated with application of a responsive, closed-loop burst. Figure 3l shows a dosing pattern including only programmed, open-loop bursts 420, 422 and 424. Each burst lasts for 4 seconds and is preceded by an off-time that lasts for 20 seconds. Thus, an off-time begins at t=0 and lasts until t=20, at which time an open-loop burst 420 begins and lasts until t=24. At t=24, the next off-time begins, and so forth. By alternating 4 second on-cycles with 20 second off-times, an on-time to off-time ratio of 1:5 is achieved and maintained.

[0044] Figure 3m shows a pattern similar to that shown in Figure 3l except it includes an unscheduled, closed-loop burst 432. The duration (i.e., on-time) of closed-loop burst 432 is not full-length (i.e., 4-seconds), however. Instead, the duration of closed-loop burst 432 is adjusted depending on the duration of the off-time that precedes it, much like that of burst 414 in Figure 3k. Because the duration of the off-time between bursts 430 and 432 is 10 seconds, and because the desired ratio of on-time to off-time is 1:5, burst 432 is 2 seconds long, followed by an off-time of 10 seconds that lasts until the next scheduled, open-loop burst 434 is applied. Again, although burst 434 is delivered as programmed, the duration of burst 434 depends on the duration of the off-time that precedes it. The duration of the off-time preceding the burst 434 is 10 seconds, so the burst 434 is 2

seconds long, thus maintaining the desired 1:5 ratio. The next off-time is 20 seconds long and is followed by the regularly scheduled burst 436, which is a full 4 seconds in duration.

[0045] As previously explained, responsive, closed-loop bursts are delivered as a result of detecting some event. In at least some cases, this event is the detection of an impending or already-occurring seizure (e.g., detected by measuring one or more cardiac parameters). Although such an event detection is used to trigger the delivery of a closed-loop burst, the timing of such an event detection also may be used to adjust the regularly scheduled open-loop dosing. For instance, if seizures tend to occur within some threshold amount of time from the ends of off-time periods but before the next scheduled burst, the off-times' duration may be reduced, thereby causing the open-loop cycles to be delivered more frequently. In another example, if seizures tend to occur within some threshold amount of time after a stimulation burst, it may be the case that the stimulation parameters are counterproductive to at least some seizure events. Thus, stimulation parameters (e.g., frequency of the electrical pulses comprising a burst) may be adjusted so that seizures become less frequent. In other embodiments, stimulation may be suspended, reduced or discontinued altogether.

[0046] In embodiments involving closed-loop stimulation, an event (such as detection of an epileptic seizure) may be based upon an algorithm that processes a body parameter such as heart rate. Depending upon the algorithm and its triggering thresholds, event detection parameters may be undesirably stringent, and may result in undesirably low amounts of stimulation. Similarly, event detection parameters may sometimes be undesirably lax, resulting in undesirably high amounts of stimulation. Accordingly, in at least some embodiments, the IMD 110 may be programmed to include minimum and maximum stimulation constraints. The IMD 110 may compare the actual amount of stimulation (i.e. electrical charge) applied to the target tissue (based, for example, on the percentage of real time that stimulation is applied, or the amount of charge delivered to the nerve within one or more time frames, or the amount of time at which stimulation above a particular frequency is applied to the nerve) to these minimum and maximum constraints to ensure that the IMD 110 is not under-stimulating or over-stimulating the patient. In case the actual amount of stimulation falls below the minimum stimulation constraint, the event detection (i.e., algorithm) parameters may be modified (i.e., lowered)

so that the actual amount of stimulation (in this case, rate of charge delivery) increases to meet or exceed the minimum stimulation constraint. Similarly, in case the actual stimulation amount exceeds the maximum stimulation constraint, the event detection parameters may be modified (i.e., increased) so that the actual amount of stimulation decreases to meet or fall below the maximum stimulation constraint. In this way, the actual amount of stimulation (on a charge and/or time basis) may be dynamically regulated into a desired and/or programmed range.

[0047] The techniques described herein may be implemented in various combinations. For example, the technique for reducing burst duration (depicted above in Figure 3i) may be combined with the technique for increasing off-time duration (illustrated in Figure 3g). This combination, in turn, may be combined with one or more additional techniques. Any and all combinations of the techniques described herein are included within the scope of this disclosure.

[0048] At a more general level, additional techniques to compensate for reduced battery life associated with responsive, closed-loop bursts are possible when the full array of programmable parameters that define electrical stimulation therapies are considered. In the embodiment of Fig. 3c, programmed pulse bursts are adjusted by resynchronizing the programmed off-time to be measured from an unplanned, closed-loop burst rather than from the previously delivered open-loop burst. In the embodiment of Fig. 3d, the off-time following a closed-loop burst is increased to cause the closed-loop burst to be considered as a substitute for the open-loop burst that would have been delivered next. Figs. 3f and 3g depict inserting additional off-time between one or more of open-loop bursts following a closed-loop burst to recover the early intervention time (EIT) associated with the closed-loop burst. Figs. 3i and 3k depict reducing the on-times of one or more open-loop bursts following a closed-loop burst to recover the additional charge (CLC) applied to the target tissue in the closed-loop burst. In Fig. 3m, the on-time of both the closed-loop and the next following open-loop burst are determined based upon their respective timing relative to the previous open-loop burst (in the case of the closed-loop burst) and the time of delivery of the closed-loop burst (in the case of the next open-loop burst), with the goal of maintaining a predetermined rate of electrical charge delivery to the target tissue.

[0049] In addition to adjusting off-time and on-time, frequency and pulse-width may also be adjusted to compensate for the CLC delivered in an unprogrammed, closed-loop burst. For example, the pulse width for some or all of the pulses of one or more open-loop bursts that follow an unprogrammed, closed-loop burst may be reduced to recover the CLC delivered in the closed-loop burst. For example, although not depicted in the Figures, the programmed pulse width of an open-loop stimulation program for a patient may be set at 250 microseconds. Following delivery of a closed-loop burst having the same on-time, frequency, pulse width, and current settings as an open-loop burst, the pulse width of the next 5 subsequent open-loop bursts may be reduced to 200 microseconds to recover the CLC applied in the closed-loop burst. Similarly, where open-loop frequency is programmed at 30 Hz, the frequency of the next 3 open-loop bursts may be reduced to 20 Hz to recover the CLC applied during a closed-loop burst (assuming that the closed-loop burst has the same one-time, frequency, pulse width and current as a programmed open-loop burst). Finally, when open-loop bursts have a programmed current of 2 milliamperes (mA), the charge delivered in a closed-loop burst having the same program parameters as the open-loop bursts may be recovered by reducing the programmed current to 1 mA for the next two open-loop bursts following the closed-loop burst. It will also be appreciated that slightly different adjustments to on-time, off-time, frequency, pulse width and/or current may be made to recover the charged applied in a closed-loop burst having different parameters (for example, a different on-time, frequency, pulse width, and/or current) than a programmed open-loop burst.

[0050] More generally, following delivery of a responsive, closed-loop burst, one of more of the off-time, on-time, pulse width and current for one or more subsequent open loop bursts may be adjusted to maintain the same rate of electrical charge delivery (i.e., coulombs of charge per unit time) as provided in programmed, open loop stimulation with no closed-loop stimulation. In other embodiments, one or more of the on-time, pulse width, and current of the closed-loop burst may also be adjusted based upon the time following the previous programmed, open-loop burst that the closed-loop burst is initiated.

[0051] The foregoing techniques may be generally described by way of method 400 of Figure 4. The method 400 begins by delivering one or more programmed, open-loop electrical bursts to a cranial nerve according to a first program (block 402). The cranial

nerve, in at least some embodiments, is the vagus nerve. The first program preferably is defined by a plurality of parameters programmed into the IMD 110, the external device 150, or some combination thereof. The method 400 further comprises delivering a responsive, closed-loop electrical burst upon detecting an event or imminent event (e.g., a seizure) or on a user's manual command (block 404). The method 400 further comprises temporarily adjusting at least one parameter defining the first program as a result of delivering the responsive, closed-loop electrical burst, thereby producing an adjusted program (block 406), where the adjusted program is characterized by restoring at least some portion of the battery life lost as a result of the delivery of the closed-loop burst. The adjusted program, like the first program, may be programmed in whole or part into the IMD 110, the external device 150, or some combination thereof. The program adjustment may employ any or all of the various techniques described herein and also may employ techniques not explicitly described herein. The method 400 still further comprises delivering an electrical pulse or pulses to the cranial nerve according to the adjusted schedule (block 408), and restoring the original program parameters of the first program (block 410).

[0052] As previously explained herein, techniques for conserving battery life are described first, followed by a description of techniques for accurately predicting battery life. The techniques for conserving battery life having been fully described, the techniques for accurately predicting battery life now follow.

[0053] Generally, in at least some battery life prediction embodiments, an estimate of battery longevity is first made based on both an open-loop stimulation program and predicted closed-loop stimulation (based on the patient's personal disease history, detector performance capabilities, and/or one or more of a variety of other factors). Subsequently, in such embodiments, the rate of closed-loop stimulation that is actually provided by the IMD 110 when the IMD 110 is implanted and operating inside the patient's body (i.e., the rate of closed-loop stimulation "in real life") is recorded and is used to adjust the estimate of battery longevity. Alternatively to the determination in step 504 of the rate at which closed-loop electrical stimulation bursts are actually applied to a cranial nerve, the IMD 110 may be programmed to deliver only open-loop therapy, but to record when closed-loop therapy would have been delivered had closed-loop therapy

been enabled. This recorded information can then be used to estimate battery longevity. The estimation may be used to adjust IMD parameters in consideration of estimated battery longevity and, if desired, closed-loop stimulation may thereafter be enabled.

[0054] In some embodiments, longevity estimates of the IMD 110 (more specifically, longevity of the power source 210) may be determined by first estimating longevity based on (1) programmed, open-loop stimulation and (2) estimates of responsive, closed-loop stimulation using the patient's personal disease history and the detection capabilities (e.g., sensitivity) of the detection logic 270. After longevity of the IMD 110 is estimated in this way, the estimate is refined by monitoring the quantity of responsive, closed-loop stimulation bursts that are delivered by the IMD 110 after the IMD 110 is implanted in the patient's body. A log of such stimulation activity may be recorded in storage 280 and later provided to the external unit 150 via the communication unit 260. Alternatively, the log may be provided in real-time to the external unit 150 via the communication unit 260. In either case, the actual closed-loop stimulation data is used to refine the initial estimate regarding longevity of the IMD 110.

[0055] In some embodiments, a different technique may be used to refine the initial estimate regarding longevity of the IMD 110. In such embodiments, the IMD 110 is programmed to deliver not only scheduled, open-loop stimulations but is further programmed to record each instance at which the IMD 110 would have delivered an unscheduled, closed-loop stimulation had it been enabled to do so. These recorded data may be provided to the external unit 150 in real-time or may be stored in storage 280 for subsequent transfer to the external unit 150. In either case, the recorded data then are used to refine the initial estimate regarding longevity of the IMD 110.

[0056] Initial estimates and refinements thereto preferably are performed by the external unit 150 but also may be performed by the IMD 110 (e.g., by the power-source controller 220, the power regulation unit 240, stimulation logic 255 or any other suitable circuit logic). In some cases, portions of the initial estimates and/or refinements may be performed on the IMD 110 with the remainder of the estimates and/or refinements performed on the external unit 150. Both the initial estimates and refined predictions are displayed or otherwise provided to an end-user of the external unit 150 (e.g., the patient's physician). The end-user may adjust IMD 110 closed-loop algorithm parameters (e.g.,

maximum and minimum stimulation thresholds at which a signal to initiate closed-loop stimulation is generated) in light of the estimated longevity. The end-user also may enable or disable responsive, closed-loop stimulations by the IMD 110.

[0057] Figure 5 shows a flow diagram of a method 500 in accordance with embodiments. The method 500 begins by calculating an IMD longevity estimate using program parameters for open-loop electrical stimulation and predictions of the rate of responsive, closed-loop electrical stimulation (block 502). The method 500 also comprises determining the actual rate at which closed-loop electrical bursts are requested to be delivered to a cranial nerve (e.g., the vagus nerve) (block 504). The action of block 504 may occur in multiple ways. For example, in some embodiments, the action of block 504 may include refining the initial calculation of block 502 based on actual closed-loop stimulation bursts that are delivered to the cranial nerve. In some embodiments, closed-loop stimulation is not implemented, and the rate of detection of events that would have triggered closed-loop stimulation had it been enabled are used instead of actual closed-loop stimulation

[0058] The method 500 further comprises re-calculating the device longevity estimate based on the program parameters for open-loop stimulation and the determination of block 504 to produce a modified device longevity estimate (block 506). The method 500 may, in some embodiments, further comprise modifying the operation of the device based on the modified device longevity calculation (block 508). In the action of block 508, the refined predictions may be provided to the end-user (e.g., a physician) so that the user may take appropriate action by modifying the operation of the IMD 110 as described above. For instance, IMD 110 parameters (e.g., maximum and minimum stimulation thresholds) may be adjusted, and closed-loop stimulation may be activated or deactivated.

[0059] The above discussion is meant to be illustrative of the principles and various embodiments of the present invention. Numerous variations and modifications will become apparent to those skilled in the art once the above disclosure is fully appreciated. It is intended that the following claims be interpreted to embrace all such variations and modifications.

CLAIMS

What is claimed is:

1. A method of providing electrical neurostimulation therapy to a patient to treat a medical condition, wherein said electrical neurostimulation therapy includes both an open-loop therapy mode and a closed-loop therapy mode and is characterized by a combined rate of electrical charge delivery to a neural structure, the method comprising:

applying a first open-loop electrical signal to the neural structure, said first open-loop signal defined by a plurality of parameters and characterized by a first open-loop rate of electrical charge delivery to the neural structure, said first open-loop rate determined by said plurality of parameters defining said first open-loop signal;

in response to a detection event, applying a closed-loop electrical signal to the neural structure, thereby causing said combined rate of electrical charge delivery to exceed said first open-loop rate;

adjusting at least one of said plurality of parameters defining said first open-loop signal to define a second open-loop electrical signal characterized by a second open-loop rate of electrical charge delivery less than said first open-loop rate;

applying said second open-loop electrical signal to said neural structure according to the second open-loop rate until said combined rate of electrical charge delivery is reduced to said first closed-loop rate; and

resuming applying said first open-loop electrical signal to said neural structure.

2. The method of claim 1, wherein said first open-loop electrical signal comprises applying a plurality of pulse bursts to said neural structure separated by an off-time period, and wherein applying said second open-loop electrical signal to said neural structure according to the second open-loop rate comprises skipping at least one burst of said first open-loop electrical signal after said application of the closed-loop electrical signal.

3. The method of claim 1, wherein said first open-loop electrical signal comprises a plurality of pulse bursts separated by a first programmed off-time period, and said second open-loop electrical signal comprises at least one pulse burst followed by a second off-time period, said method further comprising:

determining an early intervention time associated with applying the closed-loop electrical signal to said neural structure, said early intervention time comprising the difference between the first programmed off-time period and an actual off-time elapsed at the time of applying the closed-loop electrical signal to the neural structure; and

wherein said second off-time period is determined by adding at least a portion of said early intervention time to said first programmed off-time period.

4. The method of claim 1, wherein said first open-loop electrical signal comprises a plurality of electrical pulse bursts having a duration defined by a first on-time, and separated by a first programmed off-time, wherein applying said second open-loop electrical signal to said neural structure comprises delivering n electrical pulse bursts after application of said closed-loop electrical signal; and wherein said n electrical pulse bursts are defined by a second on-time less than said first on-time.

5. The method of claim 1, wherein said first open-loop electrical signal comprises a plurality of electrical pulse bursts having a duration defined by a first on-time, and separated by a first programmed off-time, and said second open-loop electrical signal comprises at least one pulse burst having a second on-time followed by a second off-time,

wherein applying said closed-loop electrical signal comprises generating a closed-loop electrical signal having a duration defined by a fraction of said first programmed off-time; and

wherein said second on-time is defined by a second fraction of said first programmed off-time.

6. A system, comprising:

detection logic adapted to detect an event; and

stimulation logic coupled to the detection logic and adapted to apply electrical stimulation therapy to a neural structure using one or both of an open-loop therapy mode and a closed-loop therapy mode, wherein said electrical stimulation therapy is characterized by a combined rate of electrical charge delivery to the neural structure;

wherein the stimulation logic applies a first open-loop electrical signal to the neural structure, the first open-loop electrical signal characterized by a plurality of parameters and by a first rate of electrical charge delivery to the neural structure that is determined by said plurality of parameters, and wherein said combined rate is said first rate;

wherein, upon receiving a notification from the detection logic as a result of the detection of said event, the stimulation logic applies a closed-loop electrical signal to the neural structure such that the combined rate exceeds said first rate;

wherein, upon applying said closed-loop signal to the neural structure, the stimulation logic adjusts one or more of said plurality of parameters to define a second open-loop electrical signal characterized by a second rate of charge delivery less than said first rate.

7. The system of claim 6 wherein the stimulation logic applies said second open-loop electrical signal to the neural structure until the combined rate is reduced to said first rate, and

wherein the stimulation logic resumes applying said first open-loop electrical signal to the neural structure.

8. The system of claim 7, wherein said first open-loop electrical signal comprises a plurality of electrical pulse bursts having a duration defined by a first on-time, and separated by a first programmed off-time, wherein, to adjust said one or parameters to define a second open-loop signal, the stimulation logic imposes an off-time duration sufficient to cause said combined rate to equal said first rate following application of the closed-loop electrical signal; and

wherein the stimulation logic resumes applying said first open-loop electrical signal to the neural structure.

9. The system of claim 6, wherein said first open-loop electrical signal comprises a plurality of electrical pulse bursts having a duration defined by a first programmed on-time, and separated by a first programmed off-time, and wherein, to adjust one or more of said plurality of parameters, the stimulation logic skips the next programmed burst of said first open-loop electrical signal after said application of the closed-loop electrical signal.

10. The system of claim 6, wherein said first open-loop electrical signal comprises a plurality of pulse bursts separated by a first programmed off-time period, and said second open-loop electrical signal comprises at least one pulse burst followed by a second off-time period;

wherein the stimulation logic determines an early intervention time associated with applying the closed-loop electrical signal to said neural structure, said early intervention time comprising the difference between the first programmed off-time period and an actual off-time elapsed at the time the closed-loop electrical signal is applied to the neural structure; and

wherein said second off-time period is determined by adding at least a portion of said early intervention time to said first programmed off-time period.

11. The system of claim 6, wherein said first open-loop electrical signal comprises a plurality of electrical pulse bursts having a duration defined by a first on-time, and separated by a first programmed off-time, and wherein, to apply said second open-loop electrical signal to said neural structure, the stimulation logic delivers n electrical pulse bursts after application of said closed-loop electrical signal; and wherein said n electrical pulse bursts are defined by a second on-time less than said first on-time.

12. The system of claim 6, wherein said first open-loop electrical signal comprises a plurality of electrical pulse bursts having a duration defined by a first on-time, and separated by a first programmed off-time, and said second open-loop electrical signal comprises at least one pulse burst having a second on-time followed by a second off-time,

wherein, to apply said closed-loop electrical signal, the stimulation logic generates a closed-loop electrical signal having a duration defined by a fraction of said first programmed off-time; and

wherein said second on-time is defined by a second fraction of said first programmed off-time.

13. A method, comprising:

applying a first open-loop electrical signal to a neural structure at a first charge delivery rate;

applying a closed-loop electrical signal to the neural structure in response to an event detection, thus causing an overall charge delivery rate to the neural structure exceeding the first charge delivery rate; and

applying a second open-loop electrical signal to a neural structure at a second charge delivery rate that is lower than the first charge delivery rate, thus causing said overall charge delivery rate to approach the first charge delivery rate.

14. The method of claim 13, wherein said first open-loop electrical signal comprises a plurality of electrical pulse bursts having a duration defined by a first programmed on-time, and separated by a first programmed off-time,

and wherein applying said second open-loop electrical signal to said neural structure at the second charge delivery rate comprises waiting for an amount of time sufficient to cause said combined rate to equal said first rate between said application of the closed-loop electrical signal and resuming delivery of said first open-loop electrical signal.

15. The method of claim 13, wherein said first open-loop electrical signal comprises a plurality of programmed electrical pulse bursts having a duration defined by a first programmed on-time, and separated by a first programmed off-time, and

wherein applying said second open-loop electrical signal to said neural structure according to the second rate comprises skipping the next programmed pulse burst of said first open-loop electrical signal after said application of the closed-loop electrical signal.

16. The method of claim 13, wherein said first open-loop electrical signal comprises a plurality of pulse bursts separated by a first programmed off-time period, and said second open-loop electrical signal comprises at least one pulse burst followed by a second off-time period, said method further comprising:

determining an early intervention time associated with applying the closed-loop electrical signal to said neural structure, said early intervention time comprising the difference between the first programmed off-time period and an actual off-time elapsed at the time of applying the closed-loop electrical signal to the neural structure; and

wherein said second off-time period is determined by adding at least a portion of said early intervention time to said first programmed off-time period.

17. The method of claim 16, further comprising adding the at least a portion of said difference to multiple off-cycles following said application of the closed-loop electrical signal.

18. The method of claim 13, wherein said first open-loop electrical signal comprises a plurality of electrical pulse bursts having a duration defined by a first on-time, and separated by a first programmed off-time, wherein applying said second open-loop electrical signal to said neural structure comprises delivering n electrical pulse bursts after application of said closed-loop electrical signal; and wherein said n electrical pulse bursts are defined by a second on-time less than said first on-time.

FIG. 1

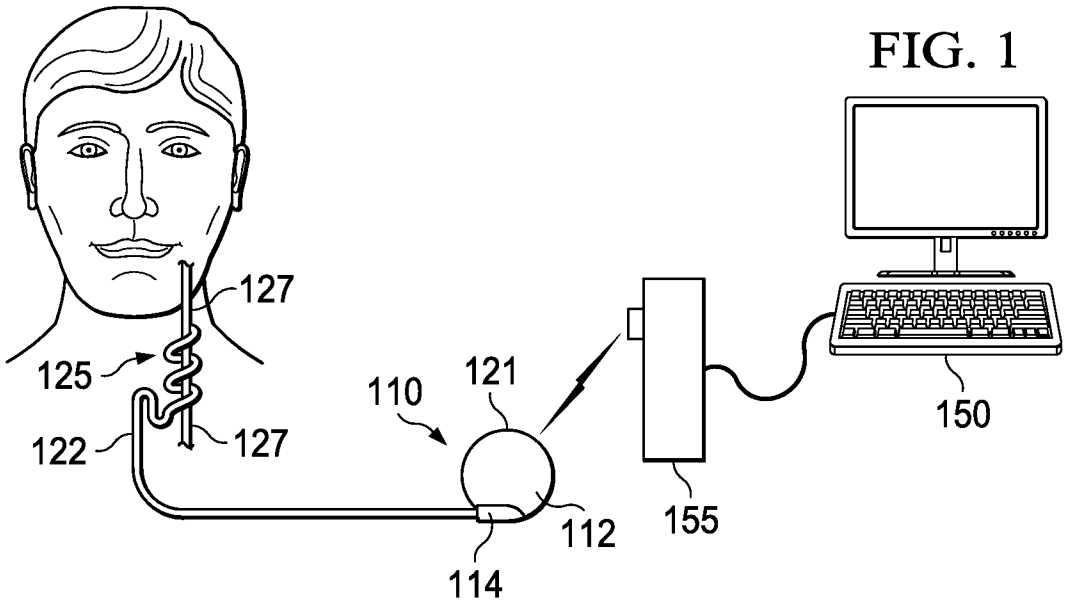
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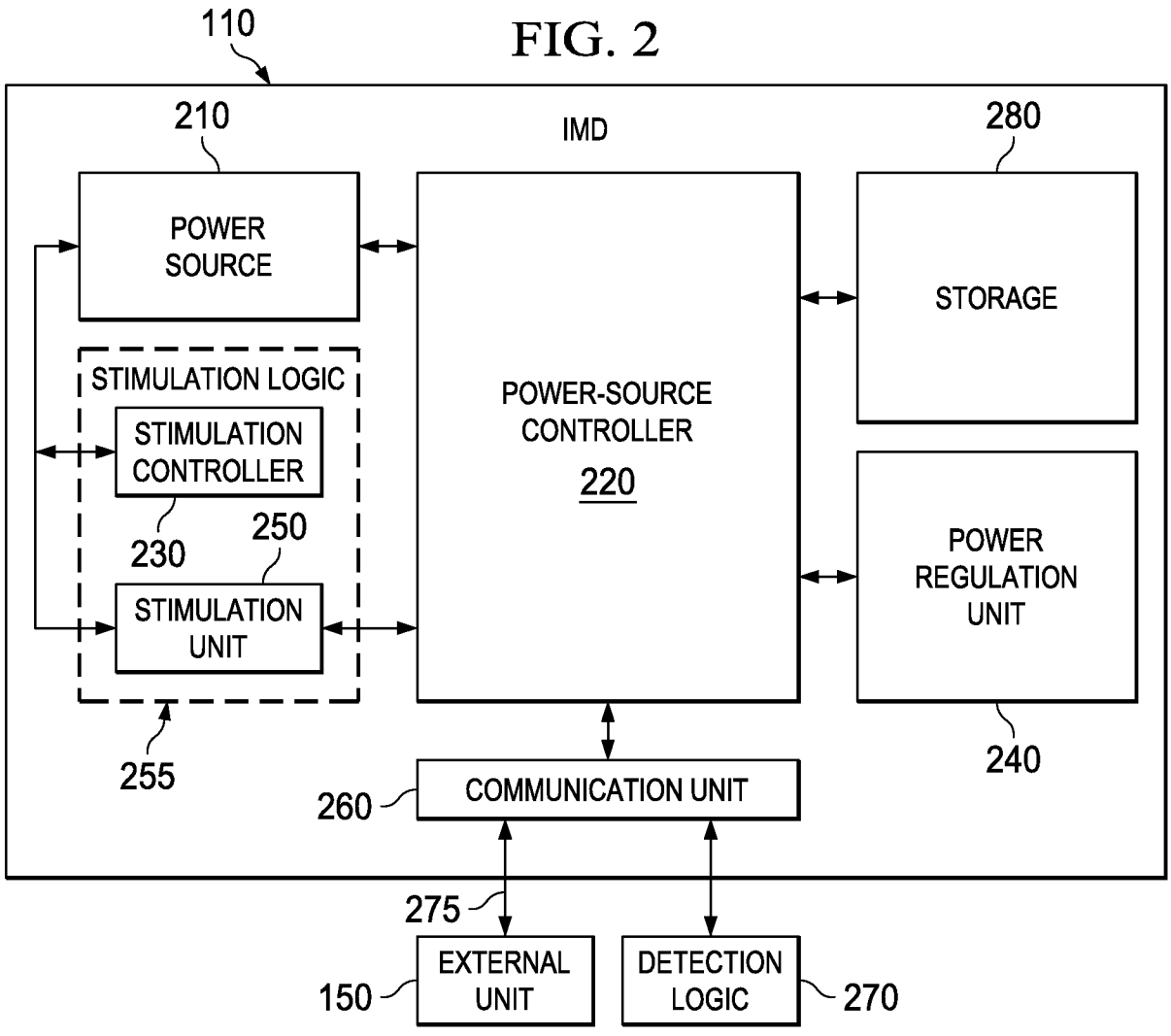
FIG. 2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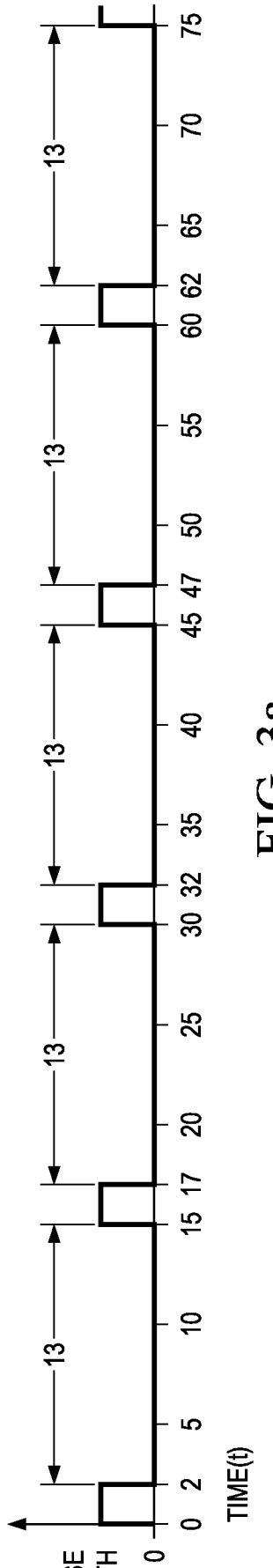


FIG. 3a
(PRIOR ART)

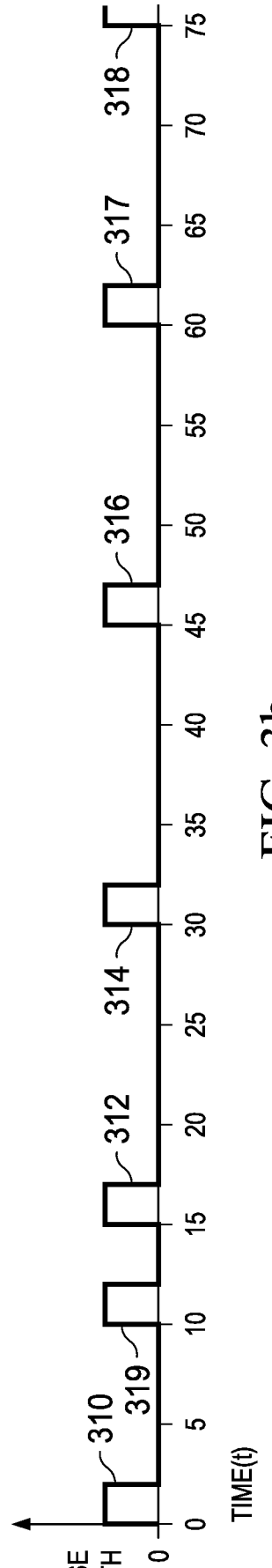
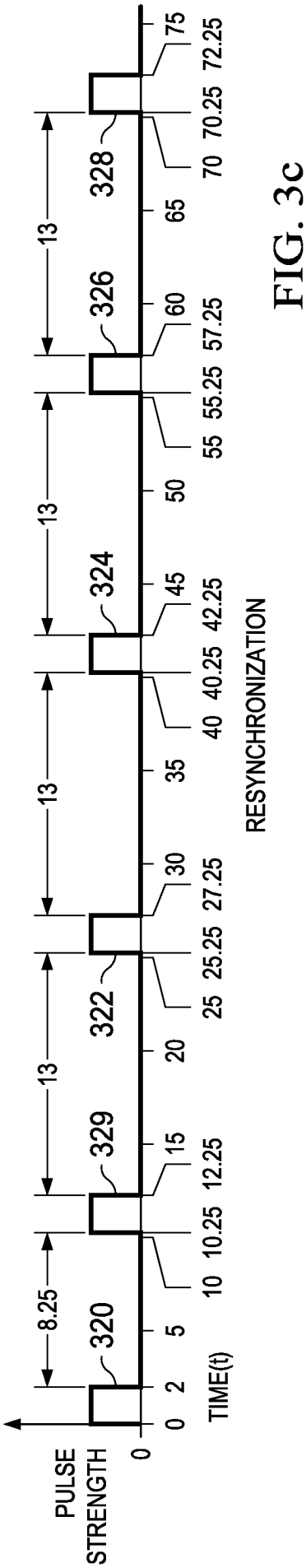


FIG. 3b
(PRIOR ART)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TIME(t)
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8.25
13
13
13
13
13
320
329
322
324
326
328
RESYNCHRONIZATION

FIG. 3c

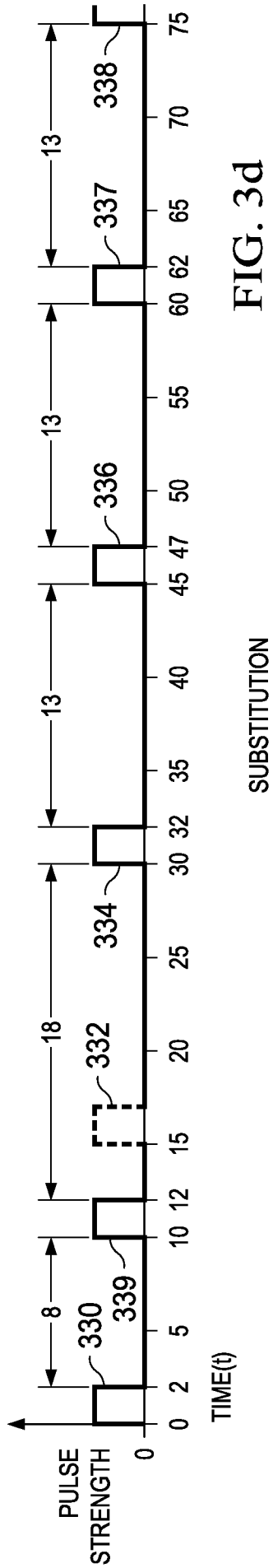
PULSE STRENGTH
0
TIME(t)
0 2 5 10 12 15 20 25 30 32 35 40 45 47 50 55 60 62 65 70 75
8
18
13
13
13
330
339
332
334
336
337
338
SUBSTITUTION

FIG. 3d

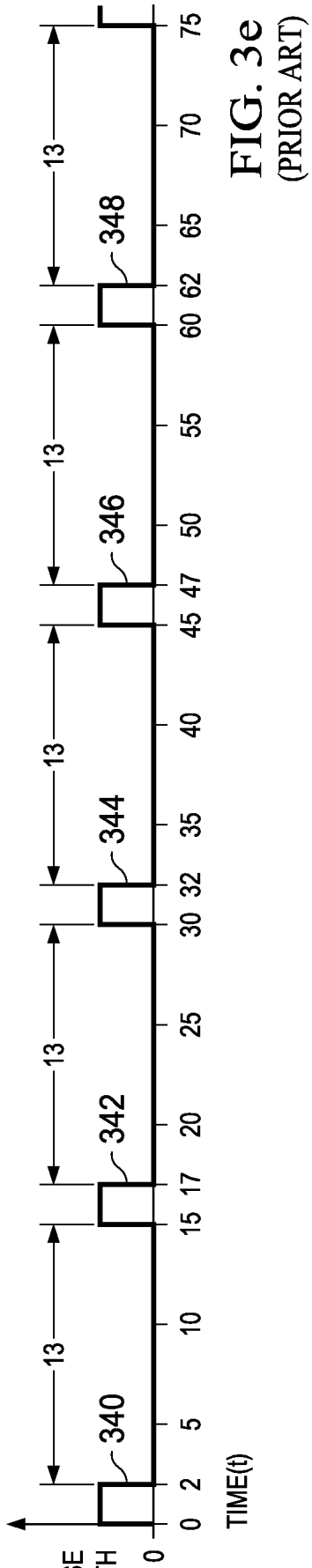

FIG. 3e
(PRIOR ART)

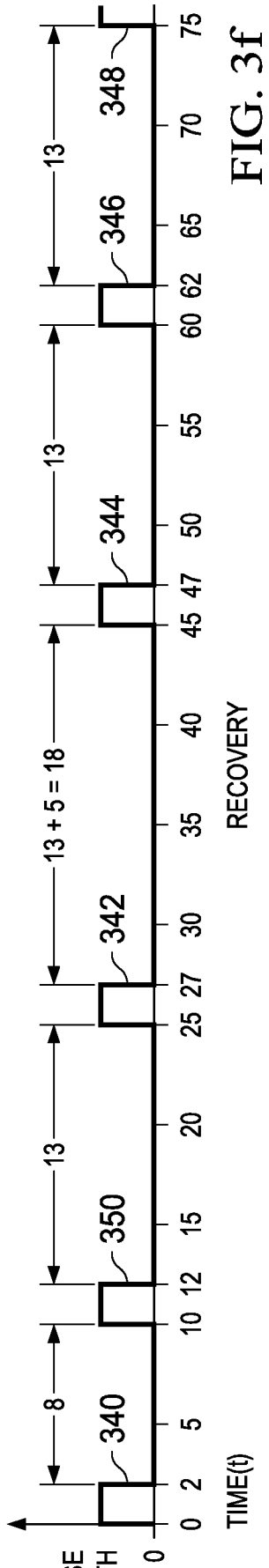

FIG. 3f

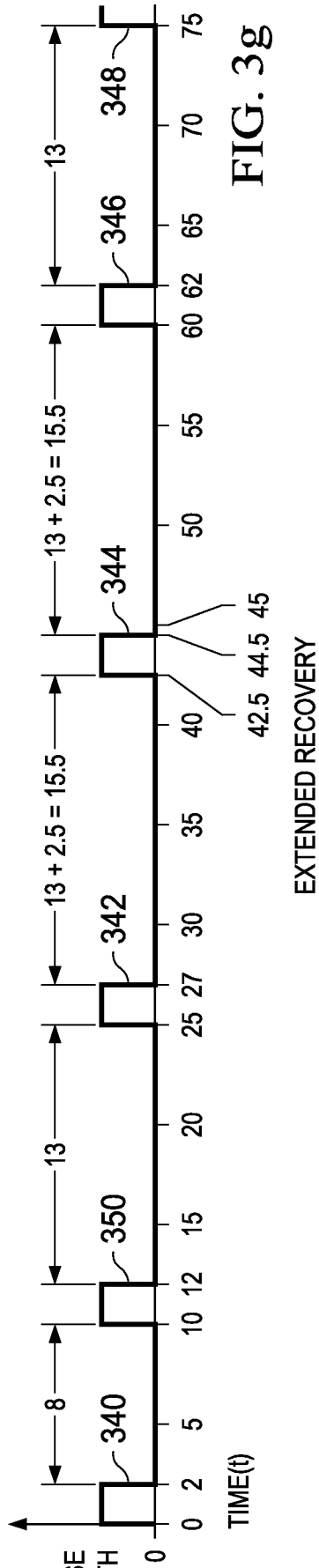

FIG. 3g

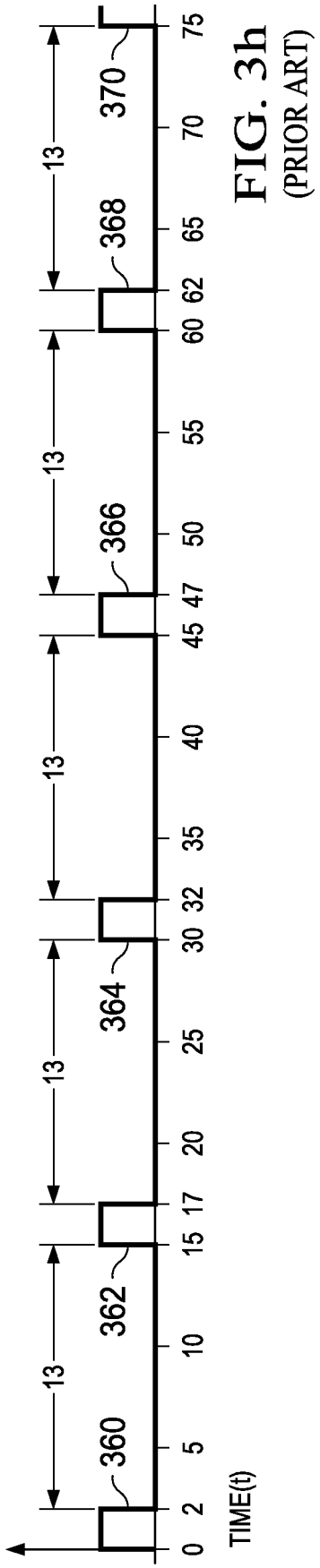

FIG. 3h
(PRIOR ART)

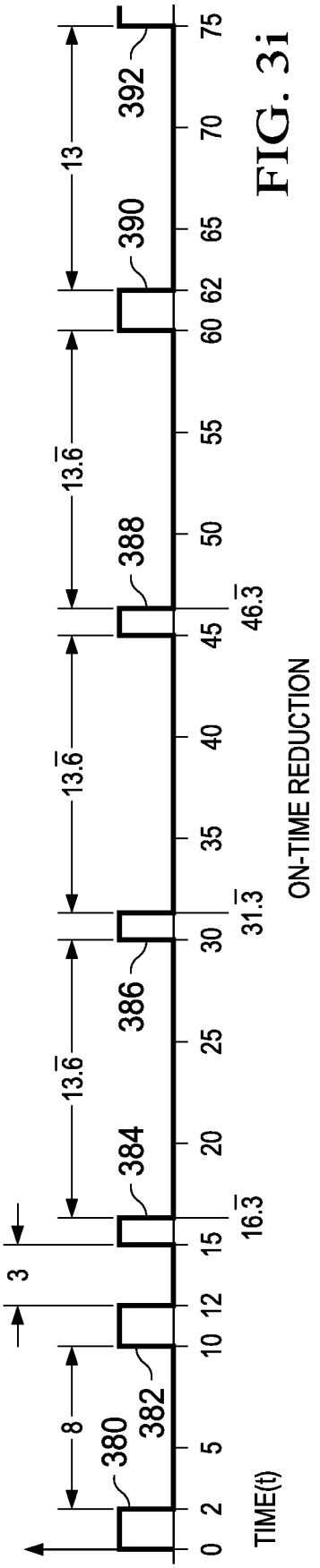

FIG. 3i

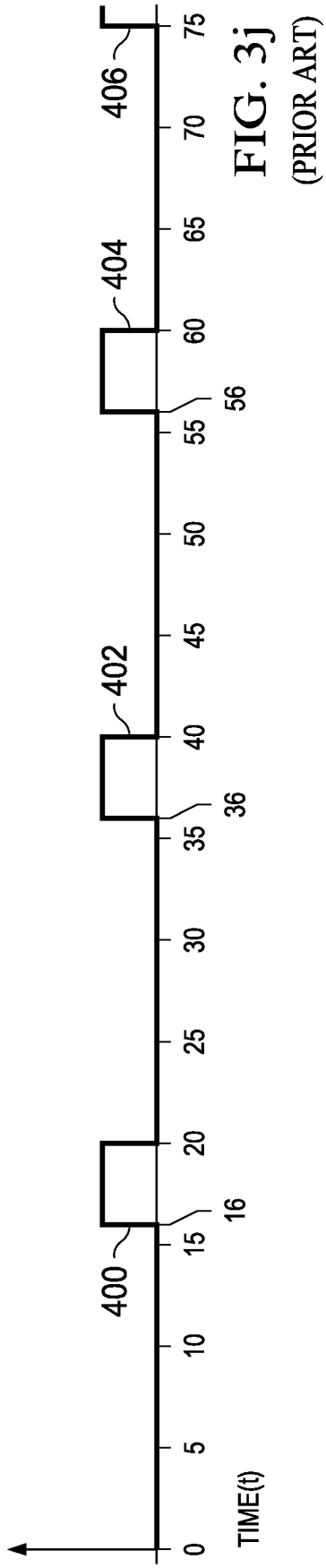

FIG. 3j
(PRIOR ART)

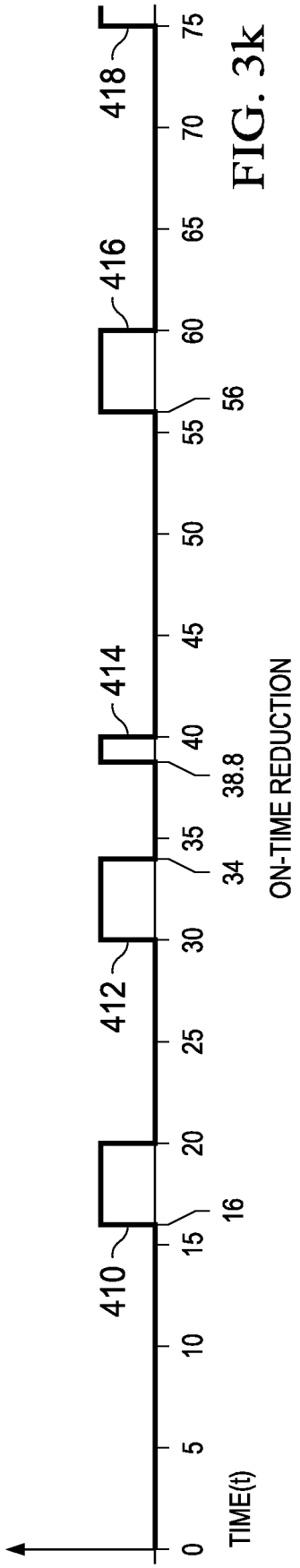

FIG. 3k

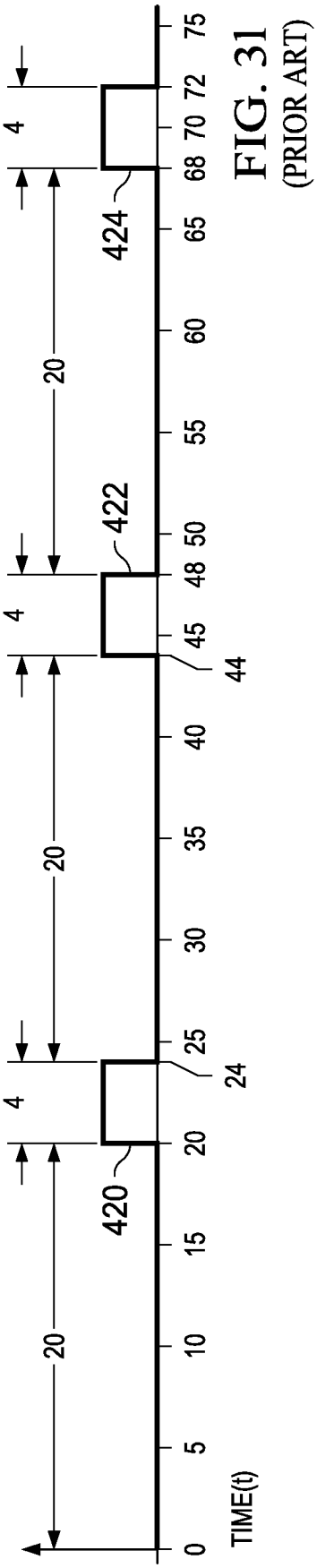

FIG. 31
(PRIOR ART)

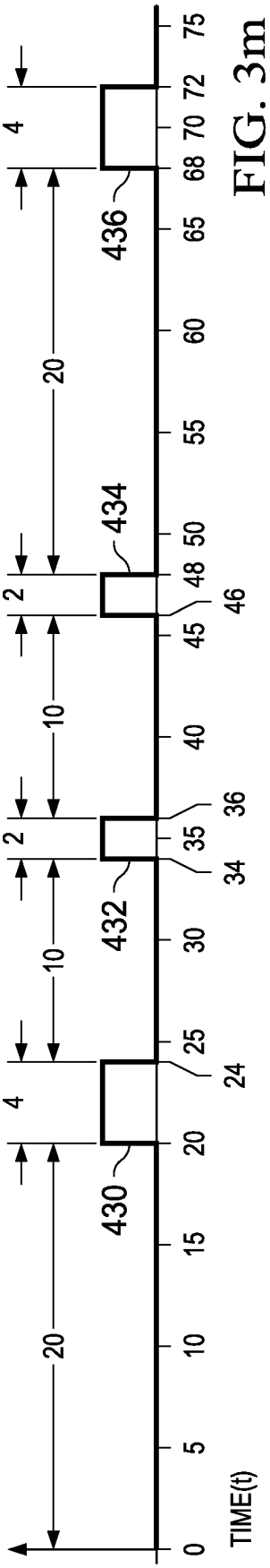

FIG. 3m

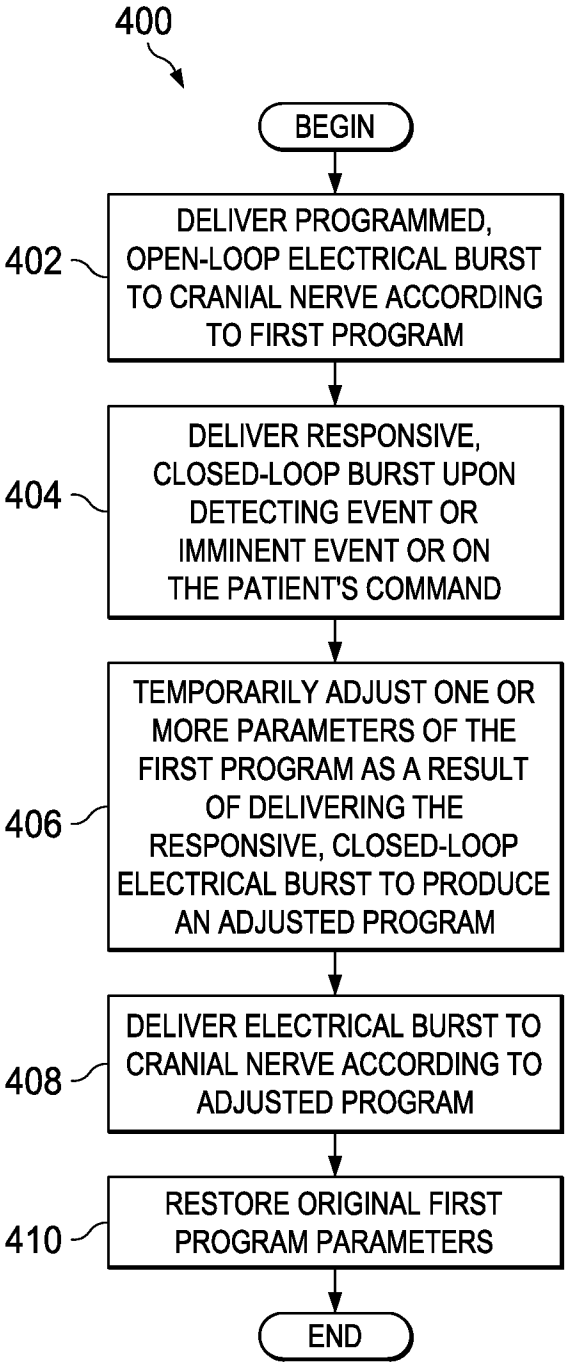
400
BEGIN
DELIVER PROGRAMMED, OPEN-LOOP ELECTRICAL BURST TO CRANIAL NERVE ACCORDING TO FIRST PROGRAM
402
DELIVER RESPONSIVE, CLOSED-LOOP BURST UPON DETECTING EVENT OR IMMINENT EVENT OR ON THE PATIENT'S COMMAND
404
TEMPORARILY ADJUST ONE OR MORE PARAMETERS OF THE FIRST PROGRAM AS A RESULT OF DELIVERING THE RESPONSIVE, CLOSED-LOOP ELECTRICAL BURST TO PRODUCE AN ADJUSTED PROGRAM
406
DELIVER ELECTRICAL BURST TO CRANIAL NERVE ACCORDING TO ADJUSTED PROGRAM
408
RESTORE ORIGINAL FIRST PROGRAM PARAMETERS
410
END

FIG. 4

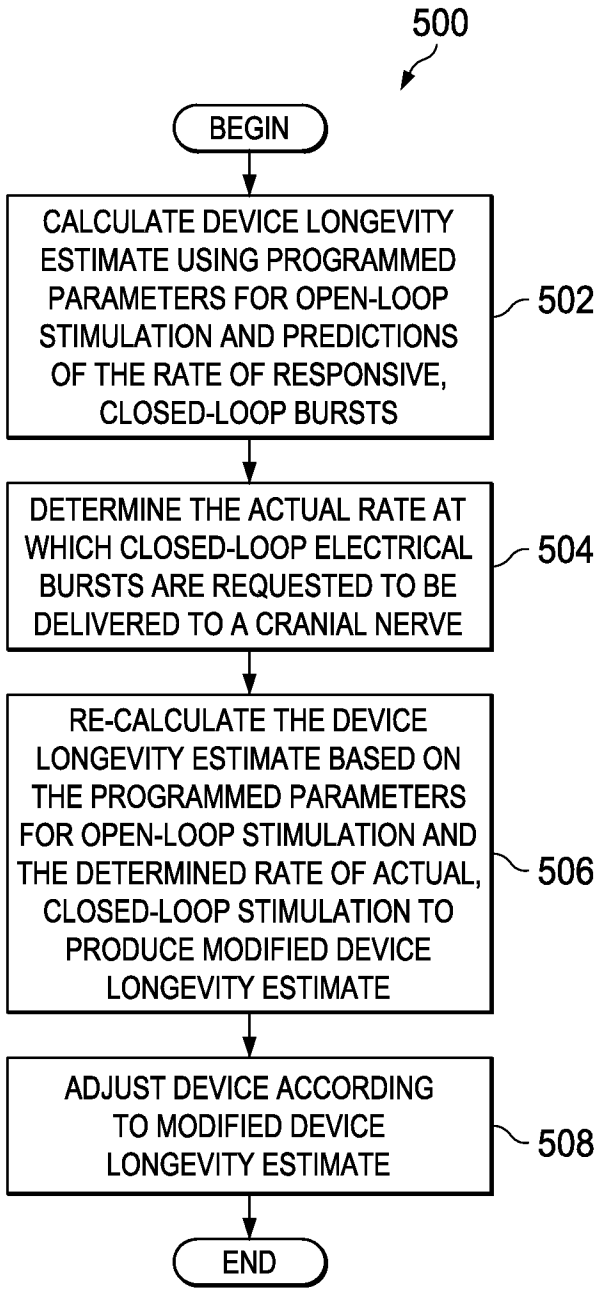
500
BEGIN
CALCULATE DEVICE LONGEVITY ESTIMATE USING PROGRAMMED PARAMETERS FOR OPEN-LOOP STIMULATION AND PREDICTIONS OF THE RATE OF RESPONSIVE, CLOSED-LOOP BURSTS
502
DETERMINE THE ACTUAL RATE AT WHICH CLOSED-LOOP ELECTRICAL BURSTS ARE REQUESTED TO BE DELIVERED TO A CRANIAL NERVE
504
RE-CALCULATE THE DEVICE LONGEVITY ESTIMATE BASED ON THE PROGRAMMED PARAMETERS FOR OPEN-LOOP STIMULATION AND THE DETERMINED RATE OF ACTUAL, CLOSED-LOOP STIMULATION TO PRODUCE MODIFIED DEVICE LONGEVITY ESTIMATE
506
ADJUST DEVICE ACCORDING TO MODIFIED DEVICE LONGEVITY ESTIMATE
508
END

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2011/033447

A. CLASSIFICATION OF SUBJECT MATTER
ADD. A61N1/36 A61N1/08 A61N1/372 A61N1/378

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

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	WO 2008/027242 A2 (CARDIAC PACEMAKERS INC [US]; BROCKWAY MARINA V [US]; LIBBUS IMAD [US];) 6 March 2008 (2008-03-06)	6
Y	claim 1 page 13, lines 5-20 figure 7	7-12

Y	WO 2004/034880 A2 (MEDTRONIC INC [US]; FREI MARK G [US]; OSORIO IVAN [US]; BHAVARAJU NARE) 29 April 2004 (2004-04-29) paragraphs [0068], [0074]	7

Y	US 2005/131467 A1 (BOVEJA BIRINDER R [US]) 16 June 2005 (2005-06-16) figure 19	8-12

	-/--	

[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
12 July 2011	25/07/2011

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, Fax: (+31-70) 340-3016	Gentil, Cédric

2

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

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2011/033447

Box No. 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.: 1-5, 13-18
because they relate to subject matter not required to be searched by this Authority, namely:

see FURTHER INFORMATION sheet PCT/ISA/210

2. [ ] Claims Nos.:
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:

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 No. 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 fees, this Authority did not invite payment of additional fees.

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 and, where applicable, the payment of a protest fee.

[ ] The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

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

Continuation of Box II.1

Claims Nos.: 1-5, 13-18

Rule 39.1(iv) PCT - Method of treatment of the human or animal being by therapy. Claims 1-5 and 13-18 define different methods for providing electrical neurostimulation therapy to a patient to treat a medical condition and therefore relate to the curing of diseases or malfunctions of the body in order to restore or maintain health. It is therefore considered that said claims define different methods of treatment of the human or animal body by therapy, for which no international search needs to be carried out (Rule 39.1(iv) PCT).

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2011/033447

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2009/015081 A2 (CVRX INC [US]; CROWLEY THOMAS P [US]; HAGEN JEFF [US]) 29 January 2009 (2009-01-29) the whole document	6-12
A	US 2009/018607 A1 (CROWLEY THOMAS PATRICK [US] ET AL) 15 January 2009 (2009-01-15) paragraphs [0068], [0074]	6-12
A	US 2009/082641 A1 (GIFTAKIS JONATHON E [US] ET AL) 26 March 2009 (2009-03-26) the whole document	6-12

2

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2011/033447

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2008027242 A2	06-03-2008	AT 499968 T	15-03-2011
		AU 2007290736 A1	06-03-2008
		EP 2066392 A2	10-06-2009
		EP 2316525 A1	04-05-2011
		JP 2010502272 A	28-01-2010
		US 2008058872 A1	06-03-2008
		US 2011009914 A1	13-01-2011
WO 2004034880 A2	29-04-2004	AU 2003285895 A1	04-05-2004
		AU 2003301256 A1	04-05-2004
		EP 1583464 A2	12-10-2005
		EP 1558131 A2	03-08-2005
		WO 2004034882 A2	29-04-2004
		US 2004152958 A1	05-08-2004
		US 2004138536 A1	15-07-2004
US 2005131467 A1	16-06-2005	NONE	
WO 2009015081 A2	29-01-2009	US 2009099625 A1	16-04-2009
US 2009018607 A1	15-01-2009	NONE	
US 2009082641 A1	26-03-2009	NONE	