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Li

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(54) **CONTROLLING ELECTRICAL STIMULATION BASED ON A SENSED STIMULATION SIGNAL**

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CPC ***A61N 1/36139*** (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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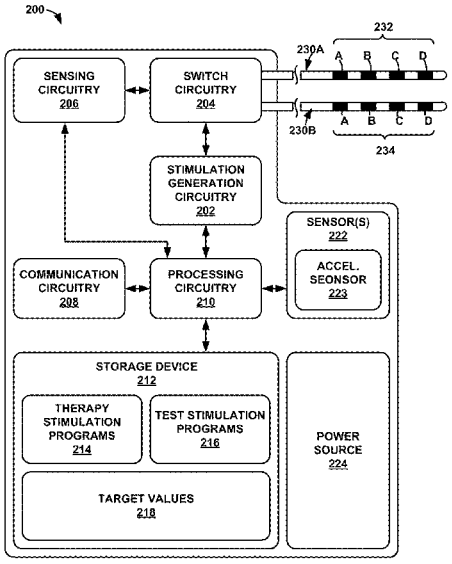
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Primary Examiner — John R Downey
Assistant Examiner — Anant A Gupta
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(57) **ABSTRACT**

This disclosure is directed to devices, systems, and techniques for controlling electrical stimulation therapy. In some examples, a medical device includes stimulation generation circuitry configured to deliver a first stimulation pulse to a patient, sensing circuitry configured to sense the first stimulation pulse, and processing circuitry. The processing circuitry is configured to determine that a value of a characteristic of the sensed first stimulation pulse exceeds a target stimulation pulse value and responsive to determining that the value of the characteristic of the sensed first stimulation pulse exceeds the target stimulation pulse value, change a first value of a parameter to a second value of the parameter that at least partially defines a second stimulation pulse deliverable by the stimulation generation circuitry after the first stimulation pulse was sensed.

27 Claims, 21 Drawing Sheets



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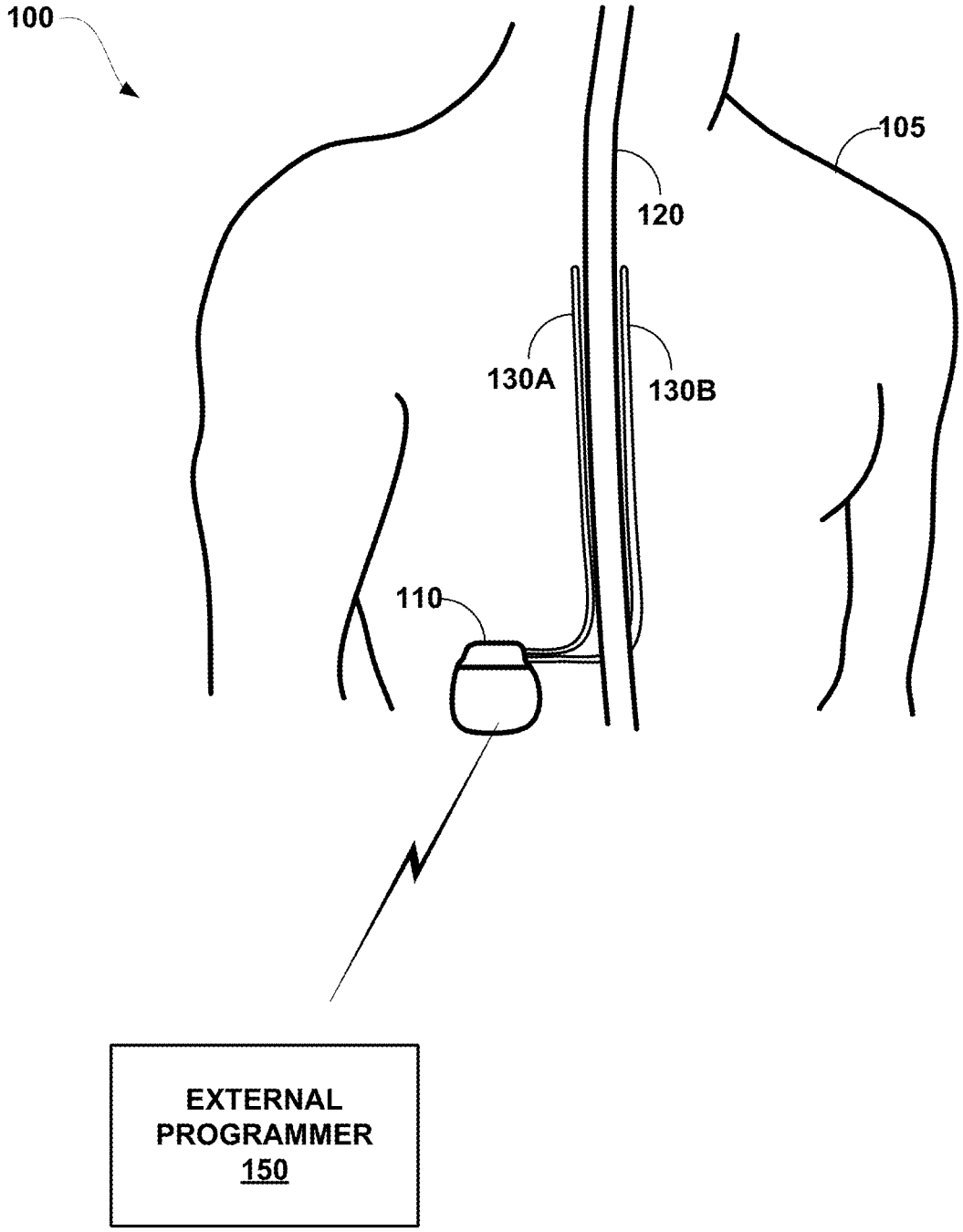


FIG. 1

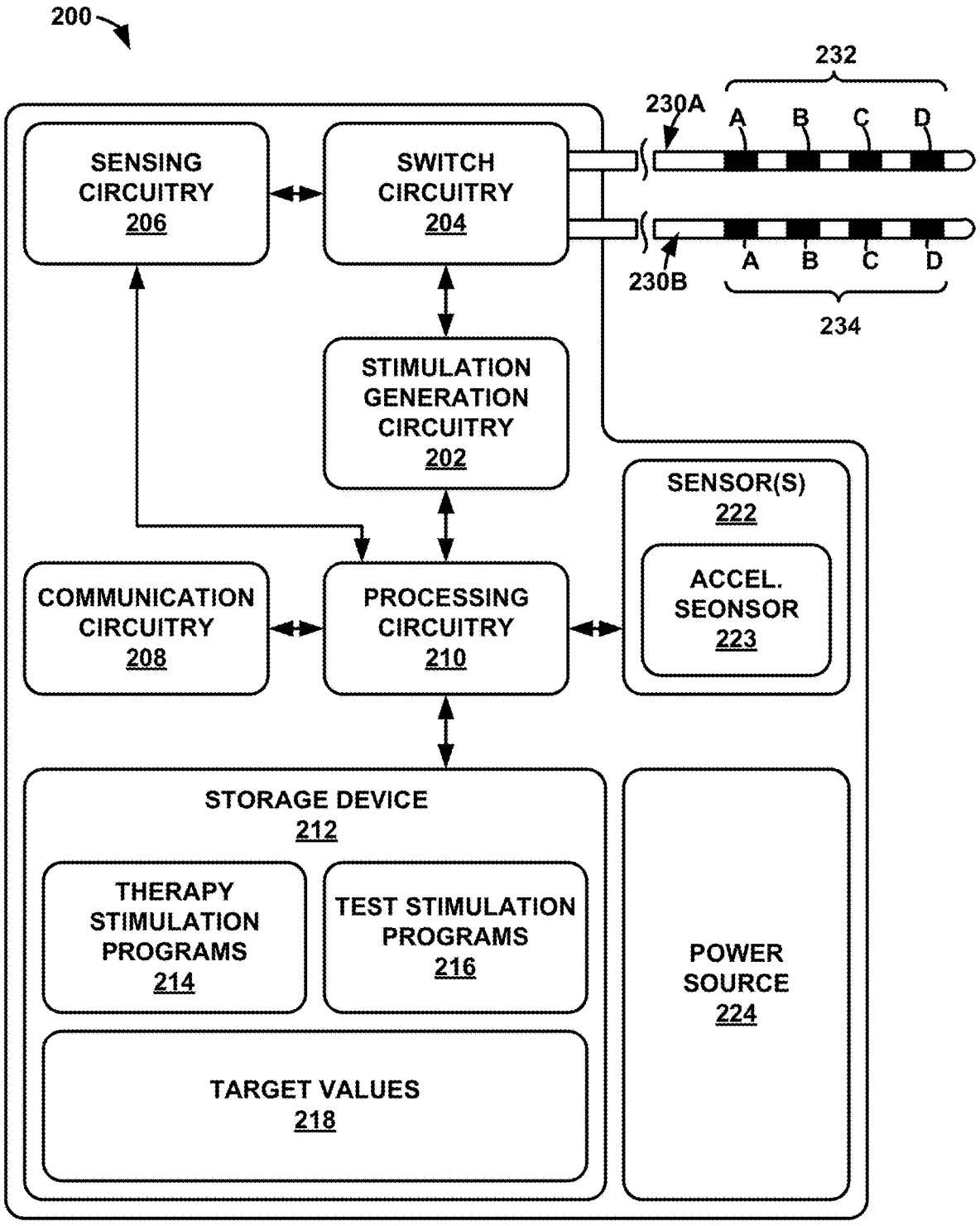

200
232
230A
A
B
C
D
SENSING CIRCUITRY 206
SWITCH CIRCUITRY 204
230B
A
B
C
D
234
STIMULATION GENERATION CIRCUITRY 202
SENSOR(S) 222
ACCEL. SEONSOR 223
COMMUNICATION CIRCUITRY 208
PROCESSING CIRCUITRY 210
STORAGE DEVICE 212
THERAPY STIMULATION PROGRAMS 214
TEST STIMULATION PROGRAMS 216
TARGET VALUES 218
POWER SOURCE 224

FIG. 2

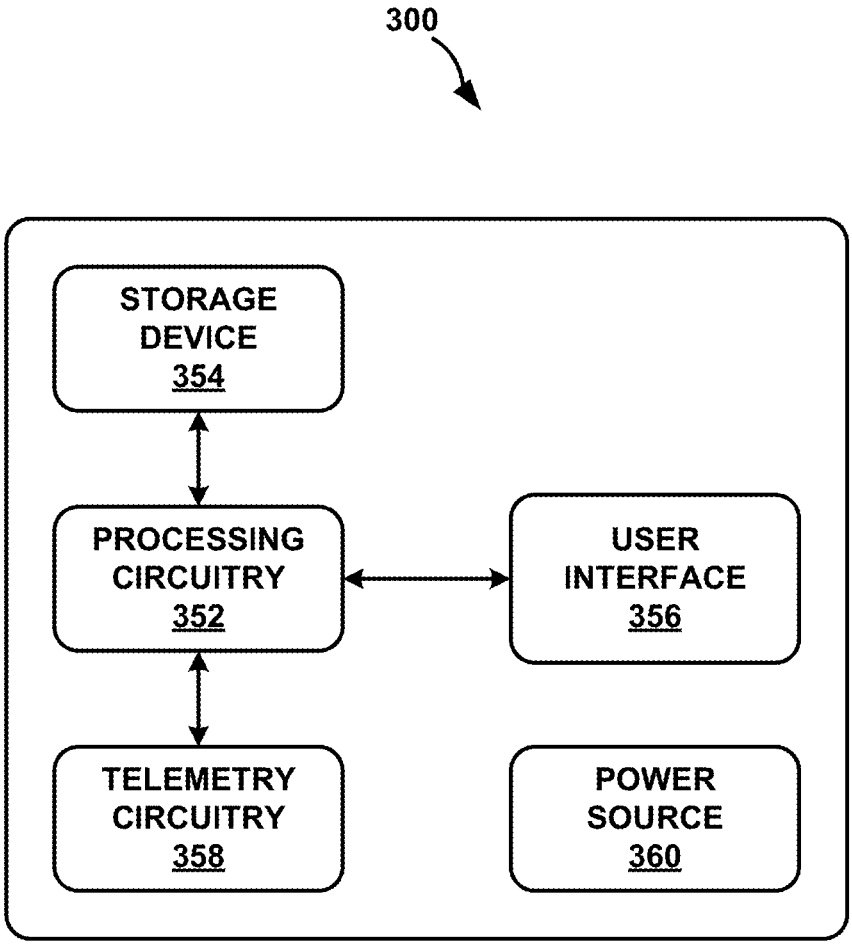

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PROCESSING CIRCUITRY 352
USER INTERFACE 356
TELEMETRY CIRCUITRY 358
POWER SOURCE 360

FIG. 3

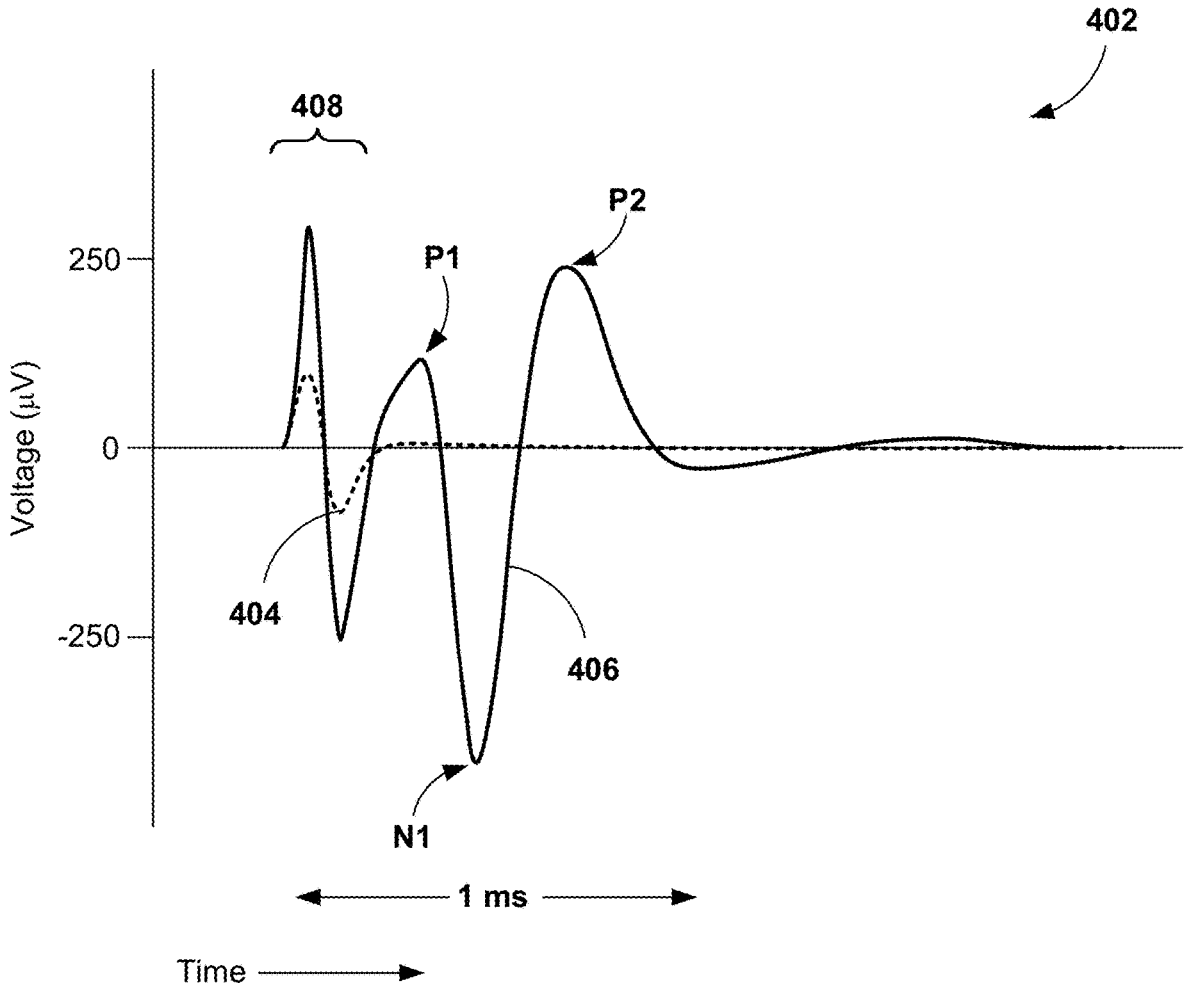


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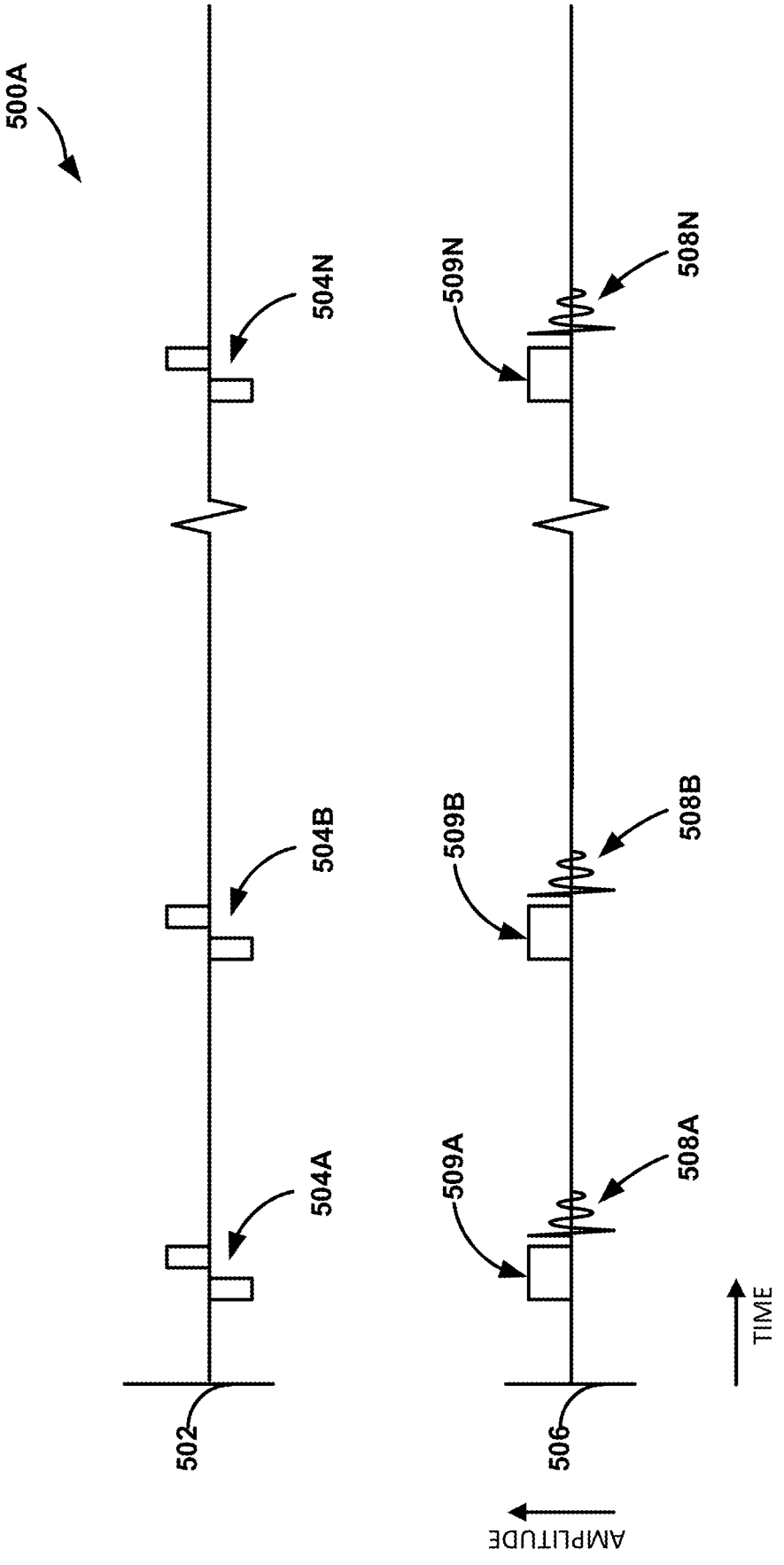

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509A
508A
506
TIME
AMPLITUDE

FIG. 5A

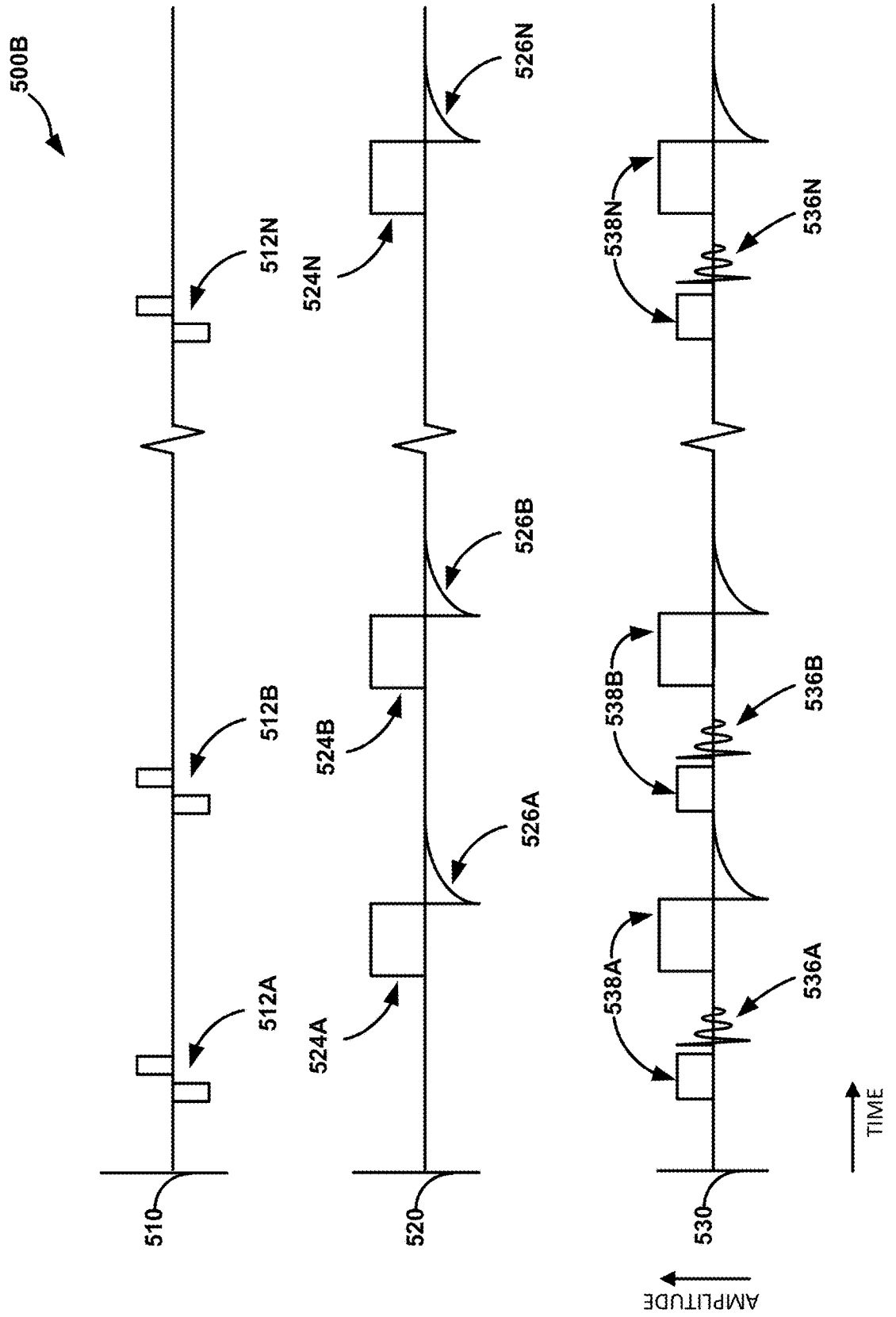

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AMPLITUDE
TIME

FIG. 5B

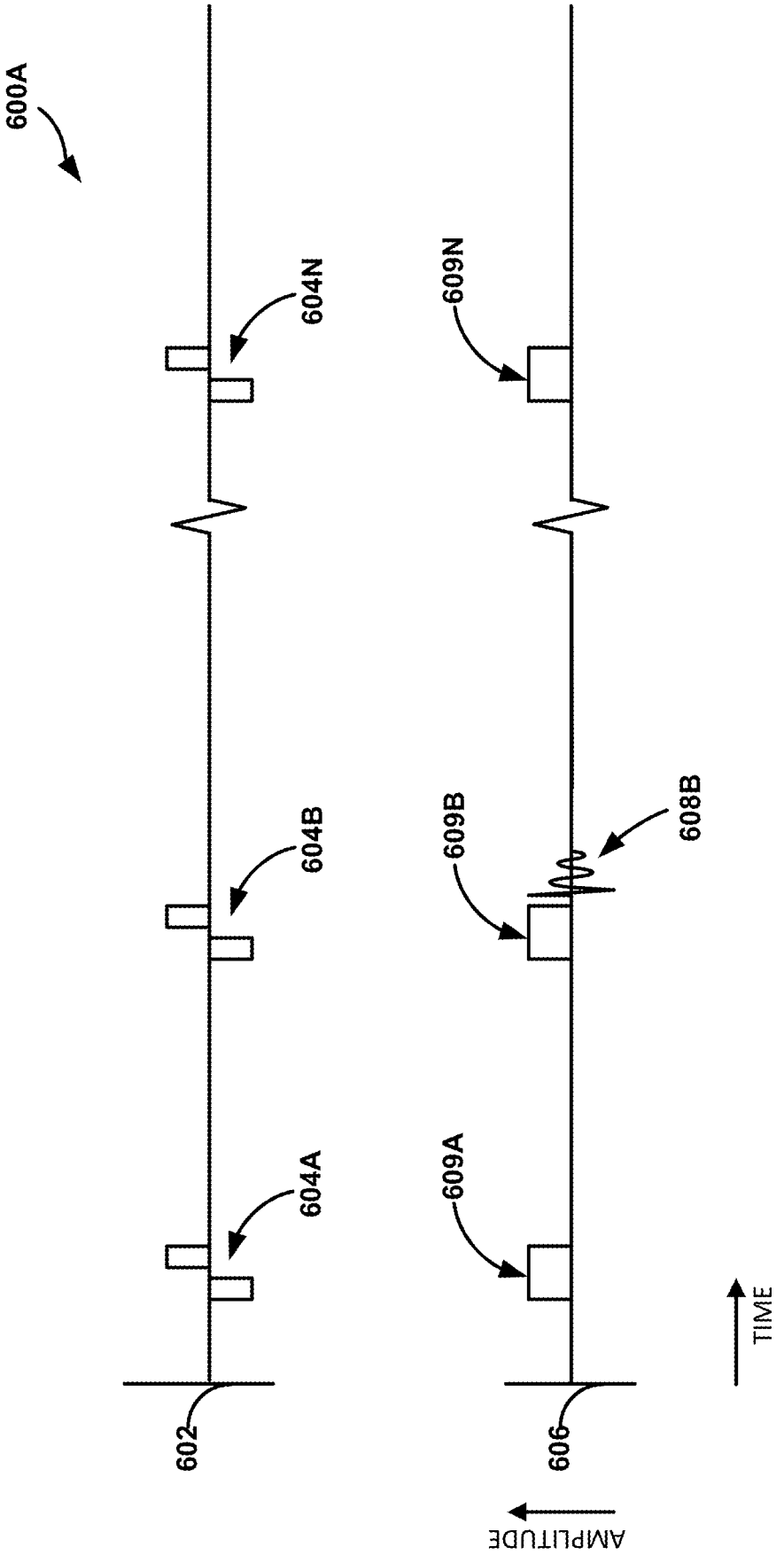

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TIME
AMPLITUDE

FIG. 6A

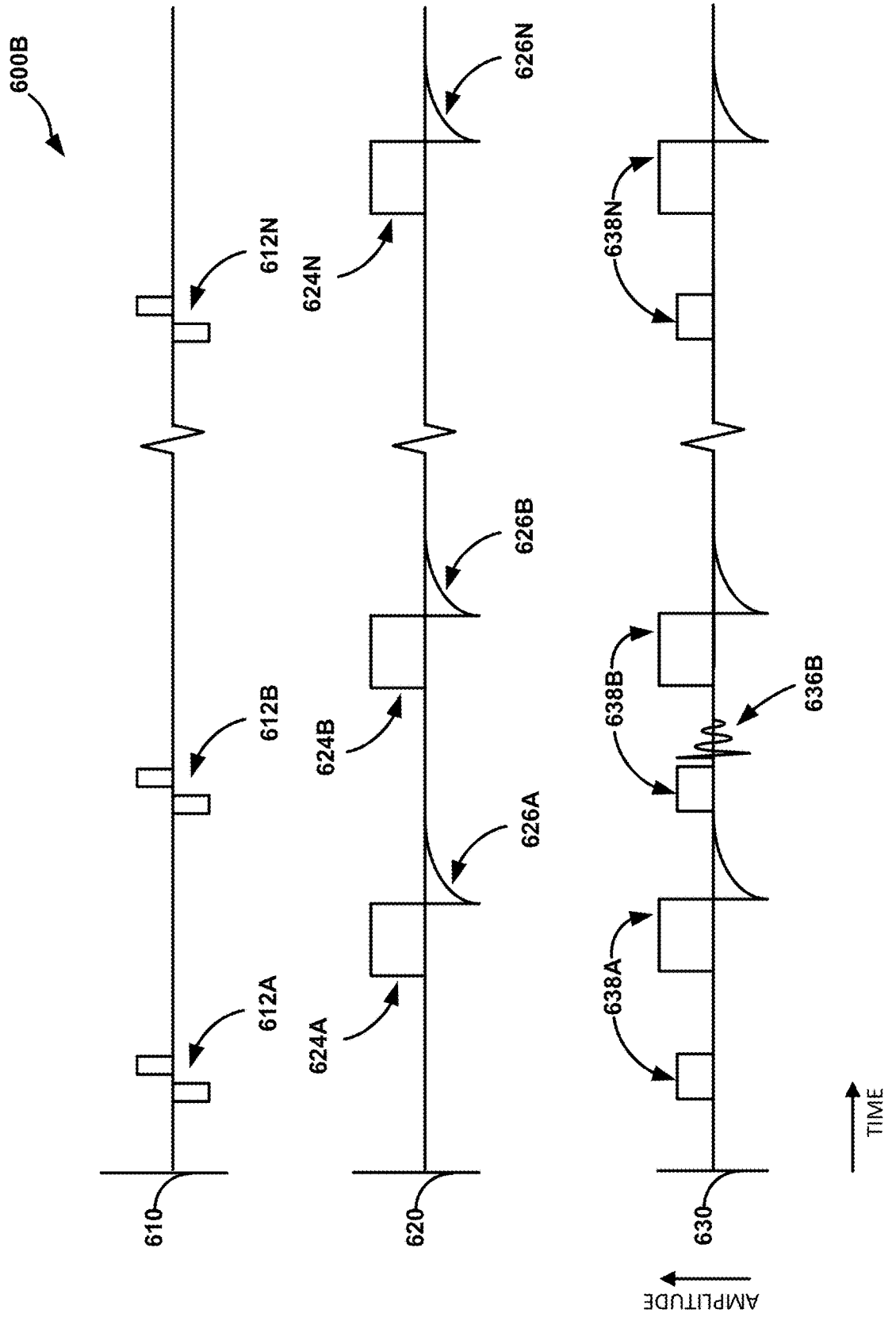

600B
612N
612B
612A
610
624N
624B
624A
620
626N
626B
626A
638N
638B
638A
636B
630
AMPLITUDE
TIME

FIG. 6B

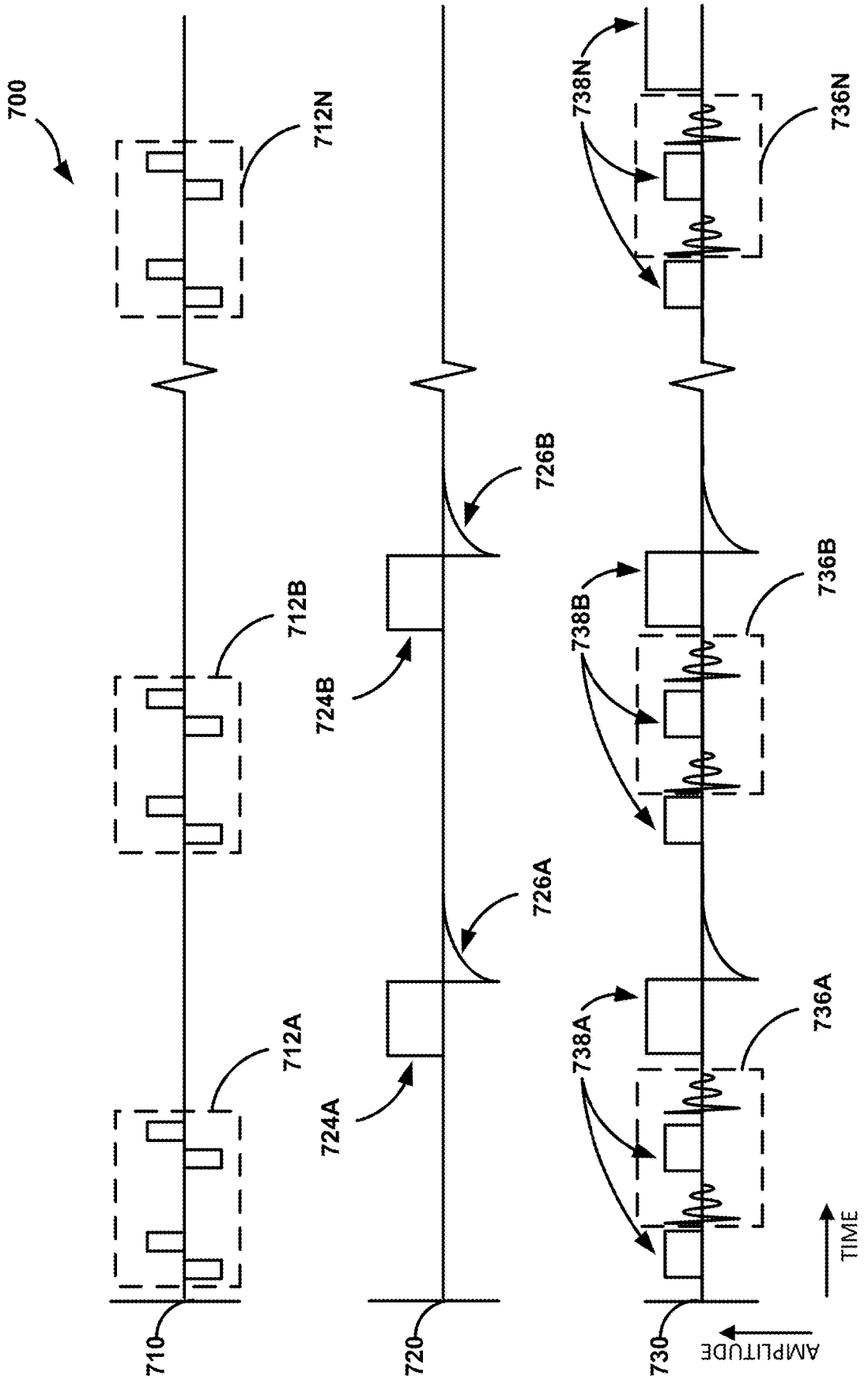

700
712N
712B
712A
710
724B
724A
726B
726A
720
738N
736N
738B
736B
738A
736A
730
AMPLITUDE
TIME

FIG. 7

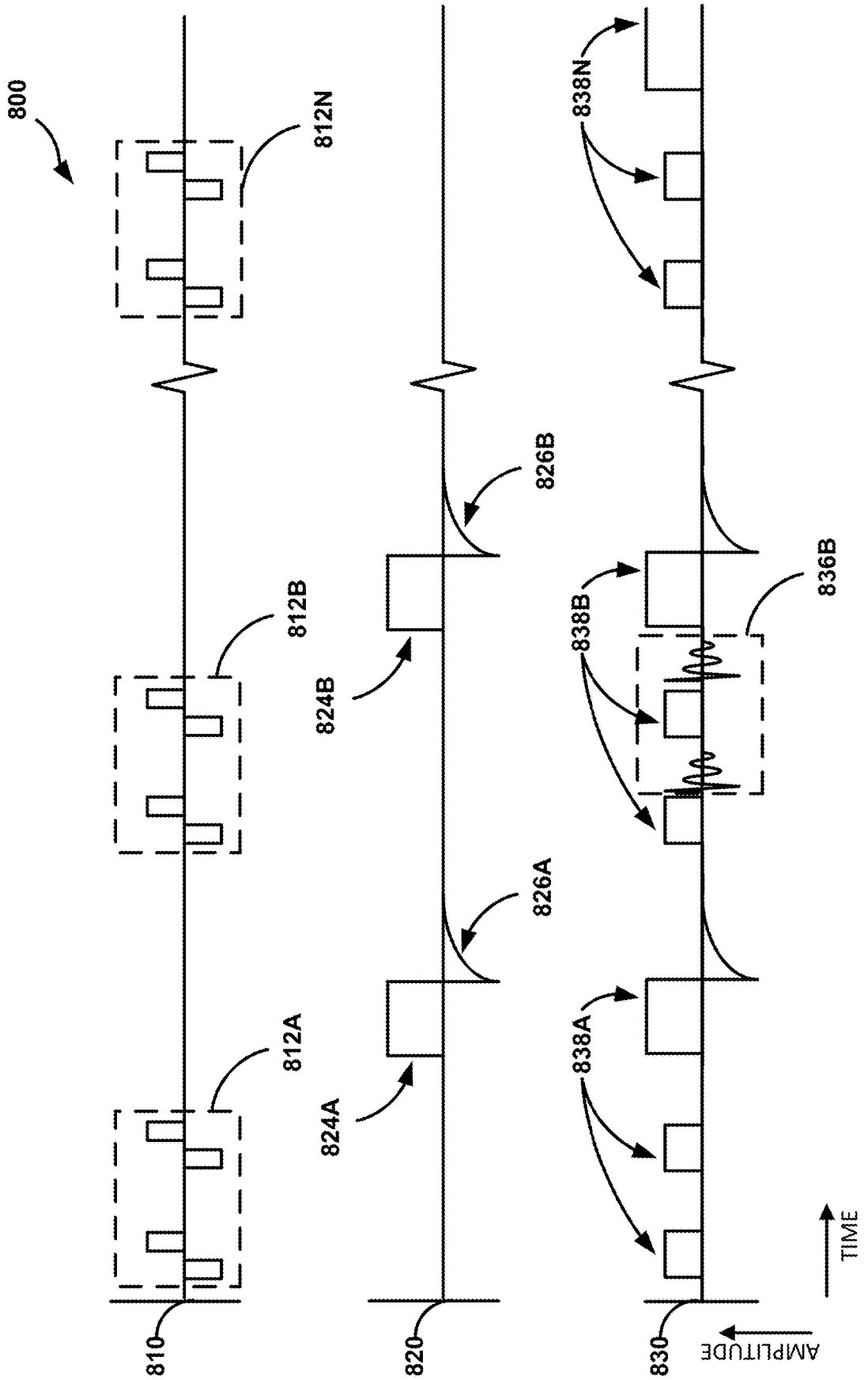

800
812N
812B
812A
824B
824A
826B
826A
838N
838B
838A
836B
810
820
830
AMPLITUDE
TIME

FIG. 8

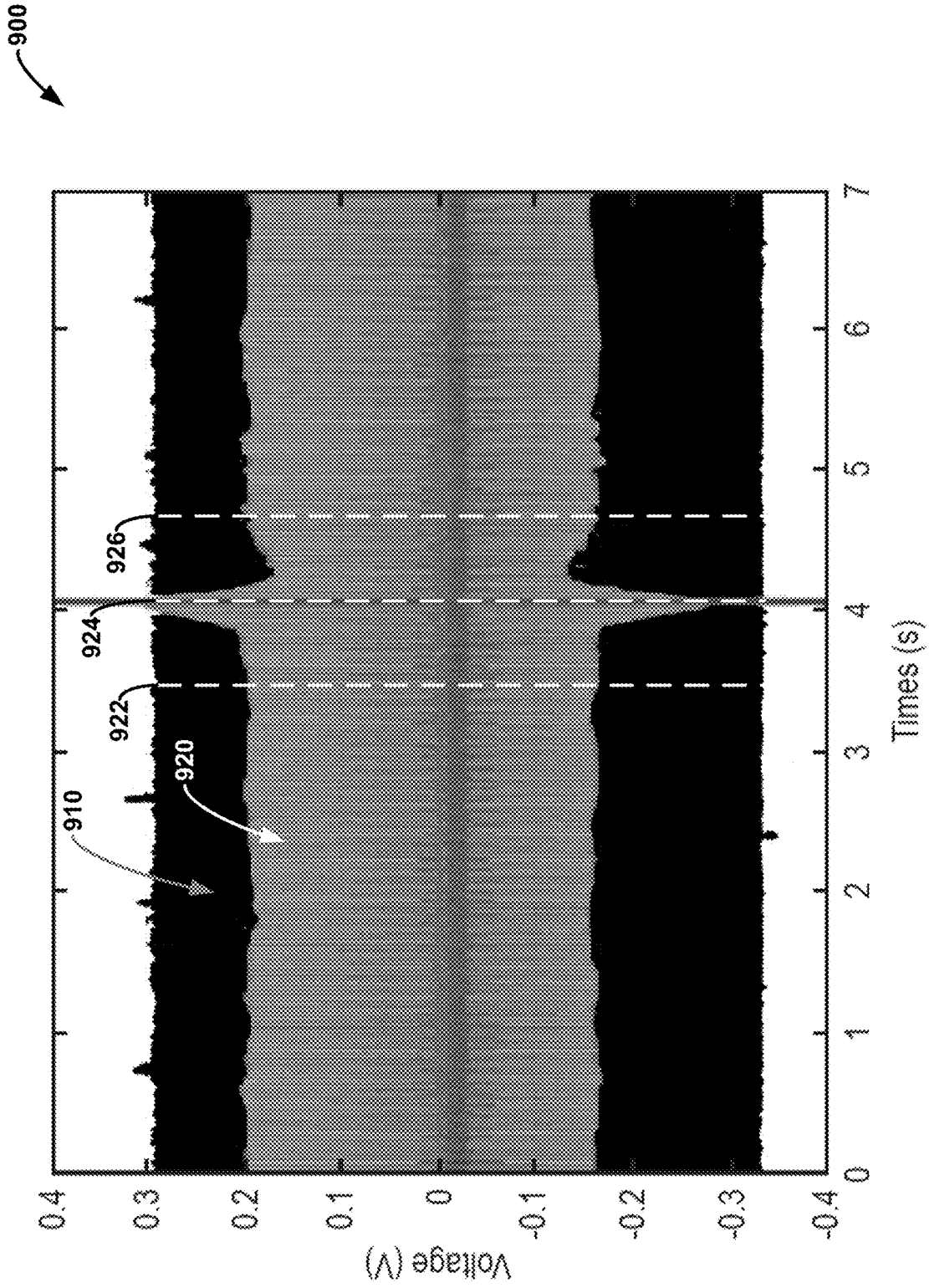

900
910
920
922
924
926
Voltage (V)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
0
1
2
3
4
5
6
7
Times (s)

FIG. 9

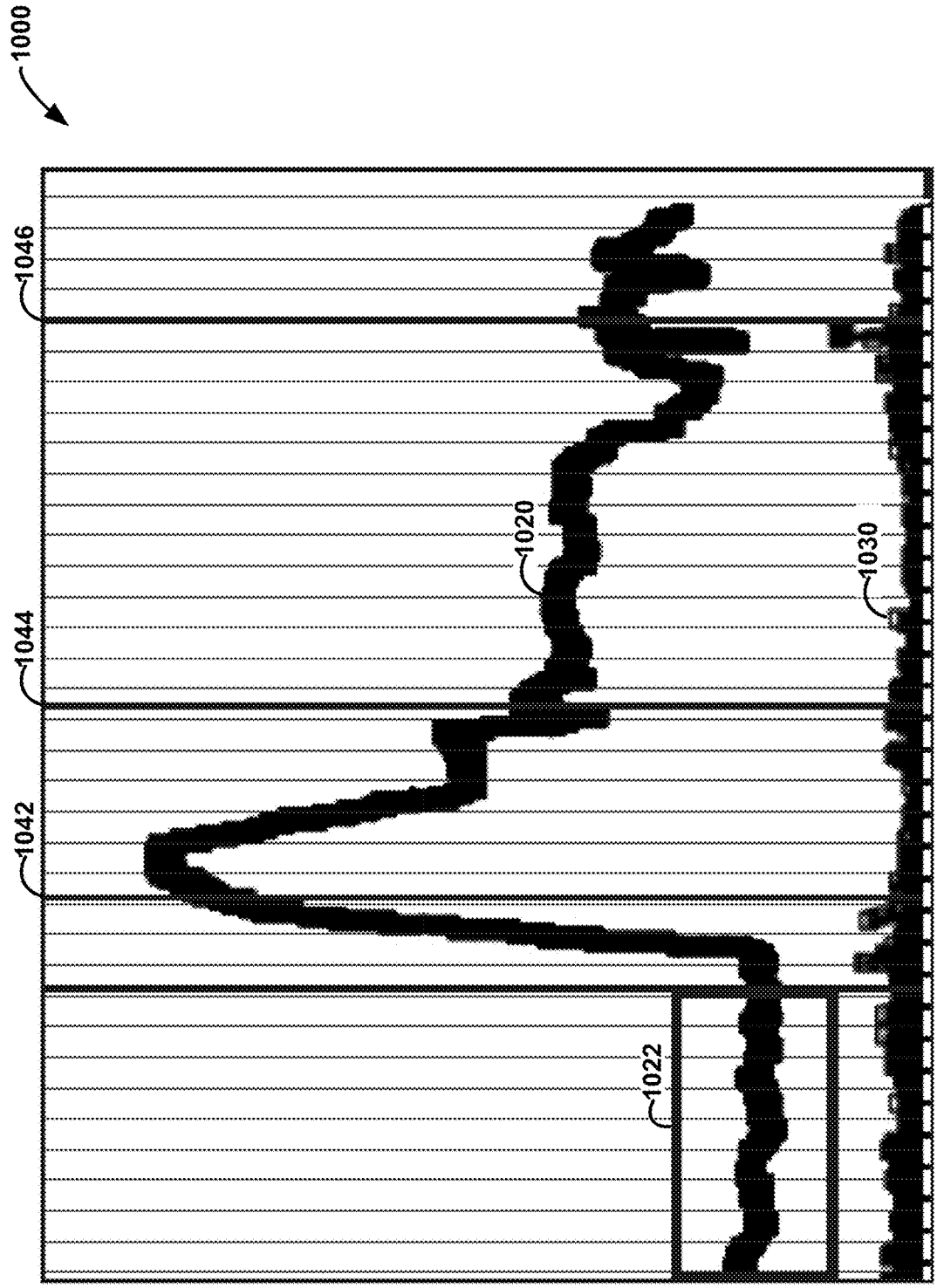


FIG. 10

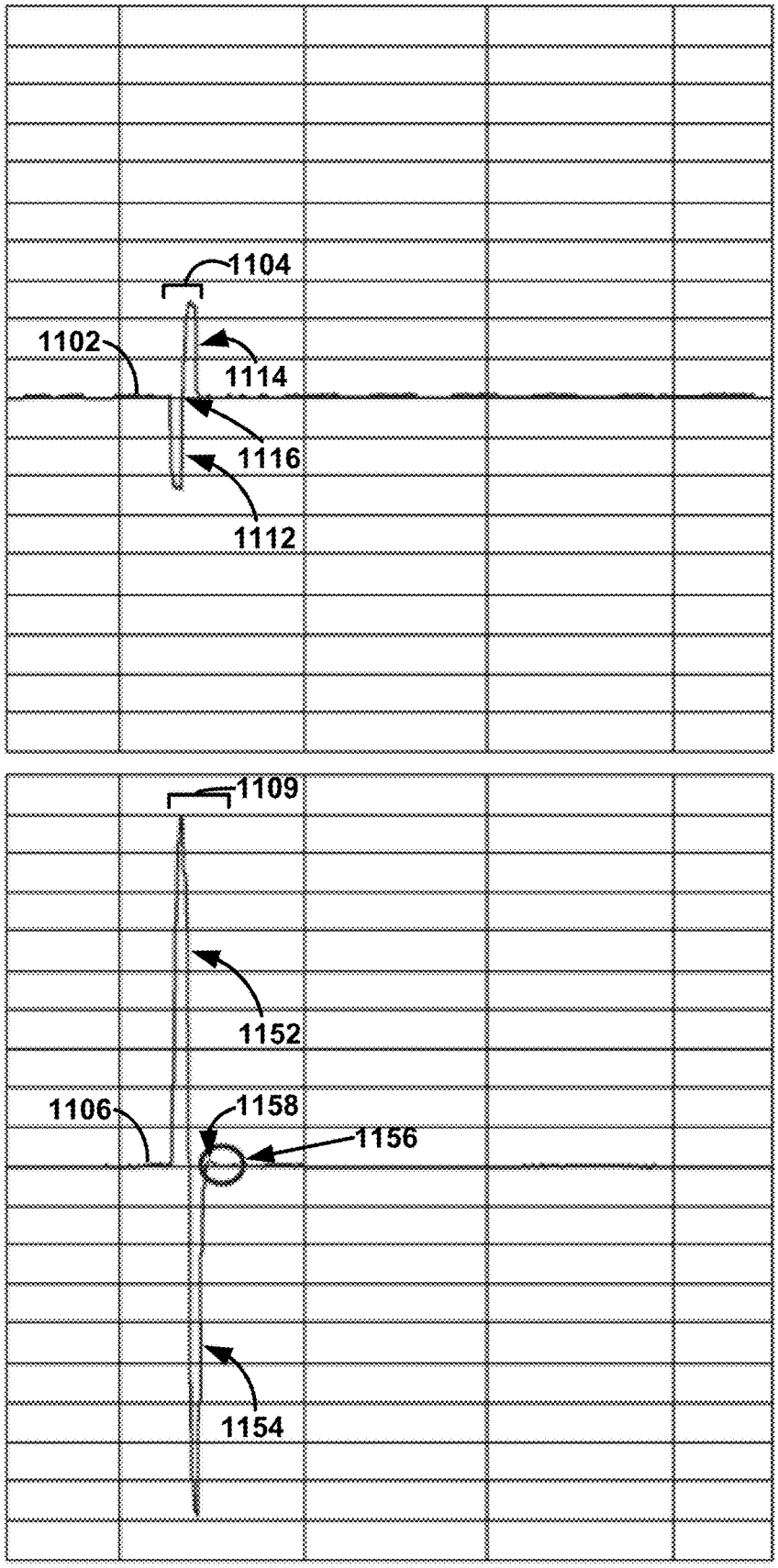


FIG. 11

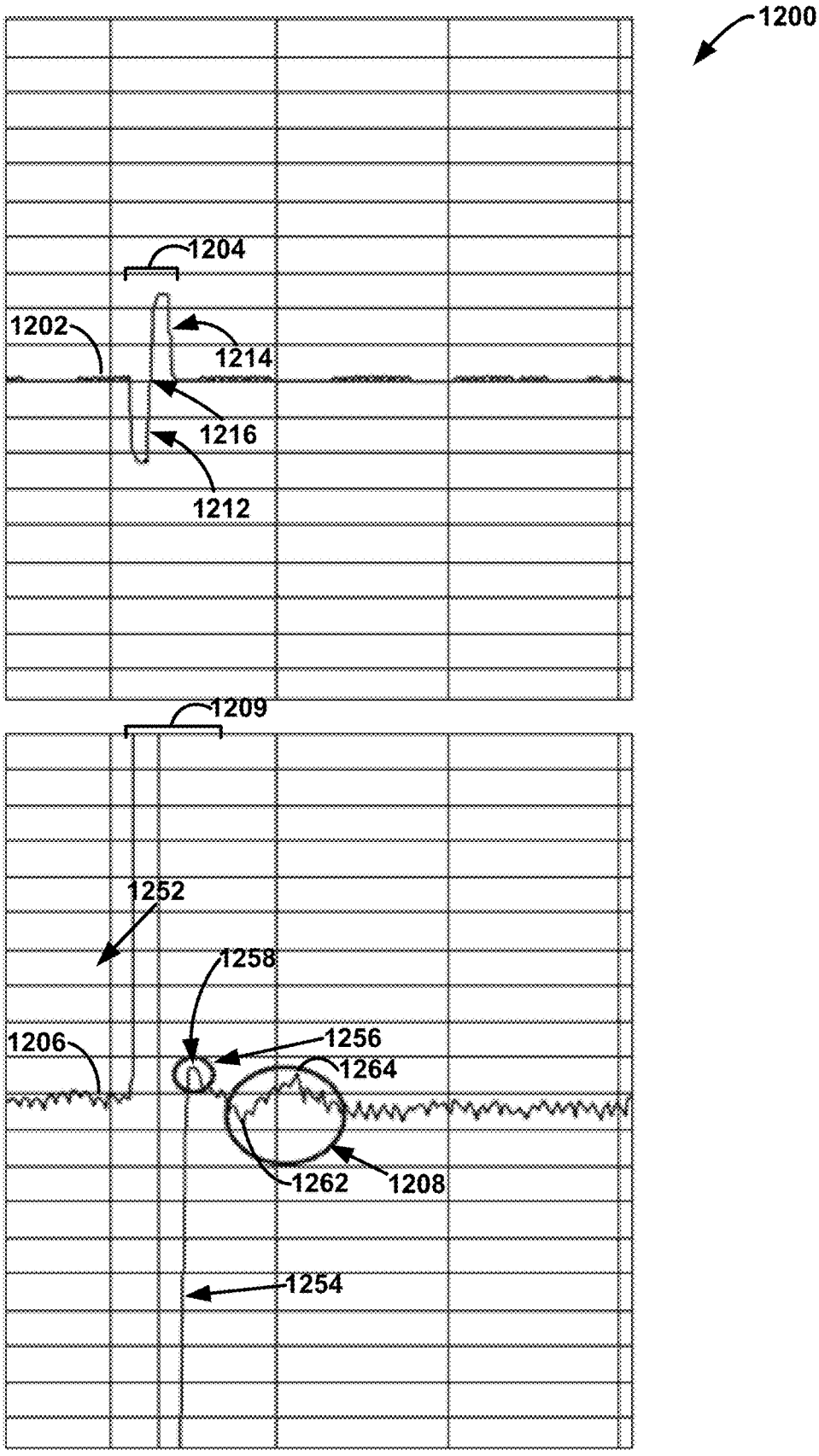

1200
1204
1202
1214
1216
1212
1209
1252
1258
1206
1256
1264
1262
1208
1254

FIG. 12

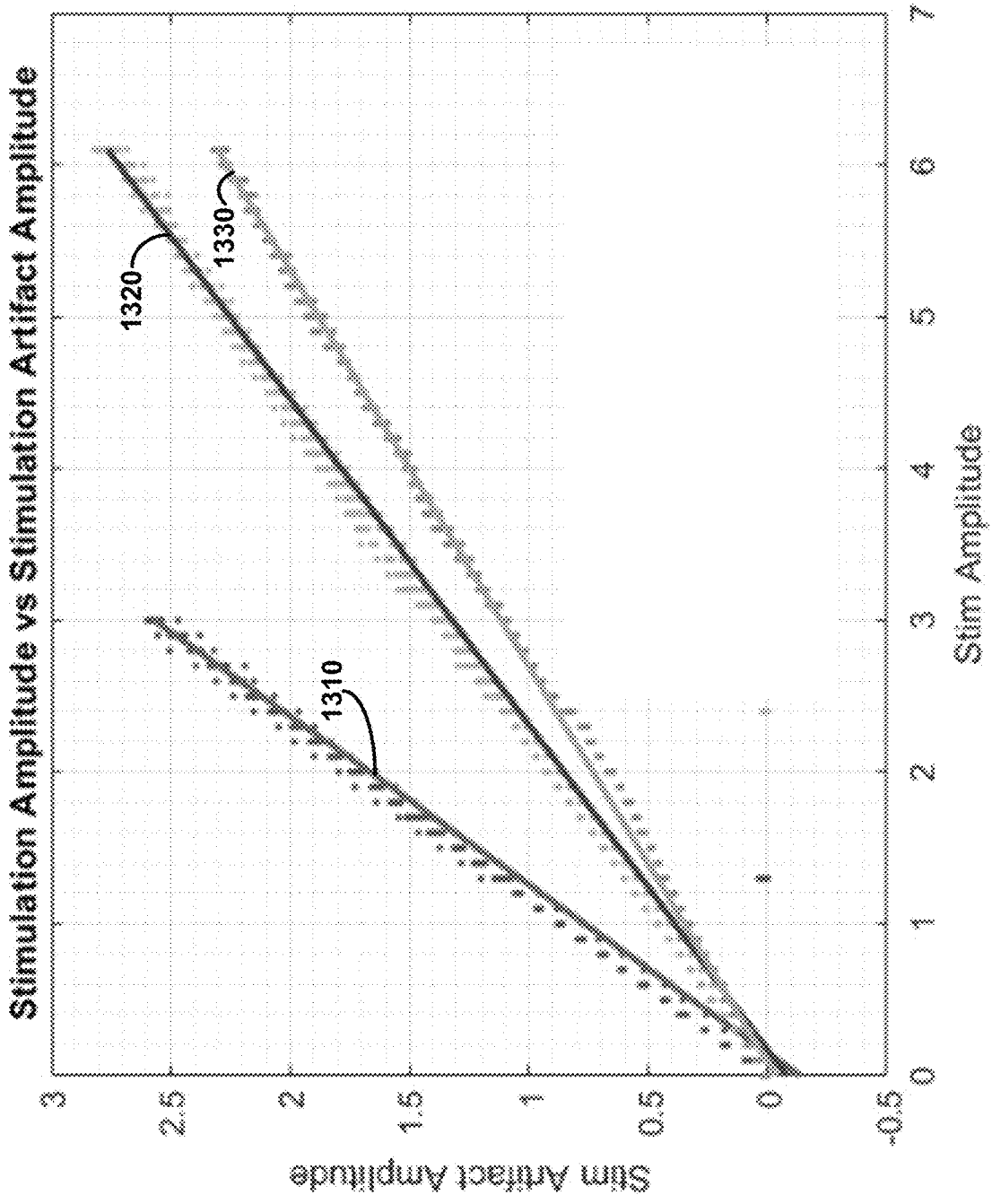

Stimulation Amplitude vs Stimulation Artifact Amplitude
Stim Artifact Amplitude
Stim Amplitude
1320
1330
1310
3
2.5
2
1.5
1
0.5
0
-0.5
0
1
2
3
4
5
6
7

FIG. 13

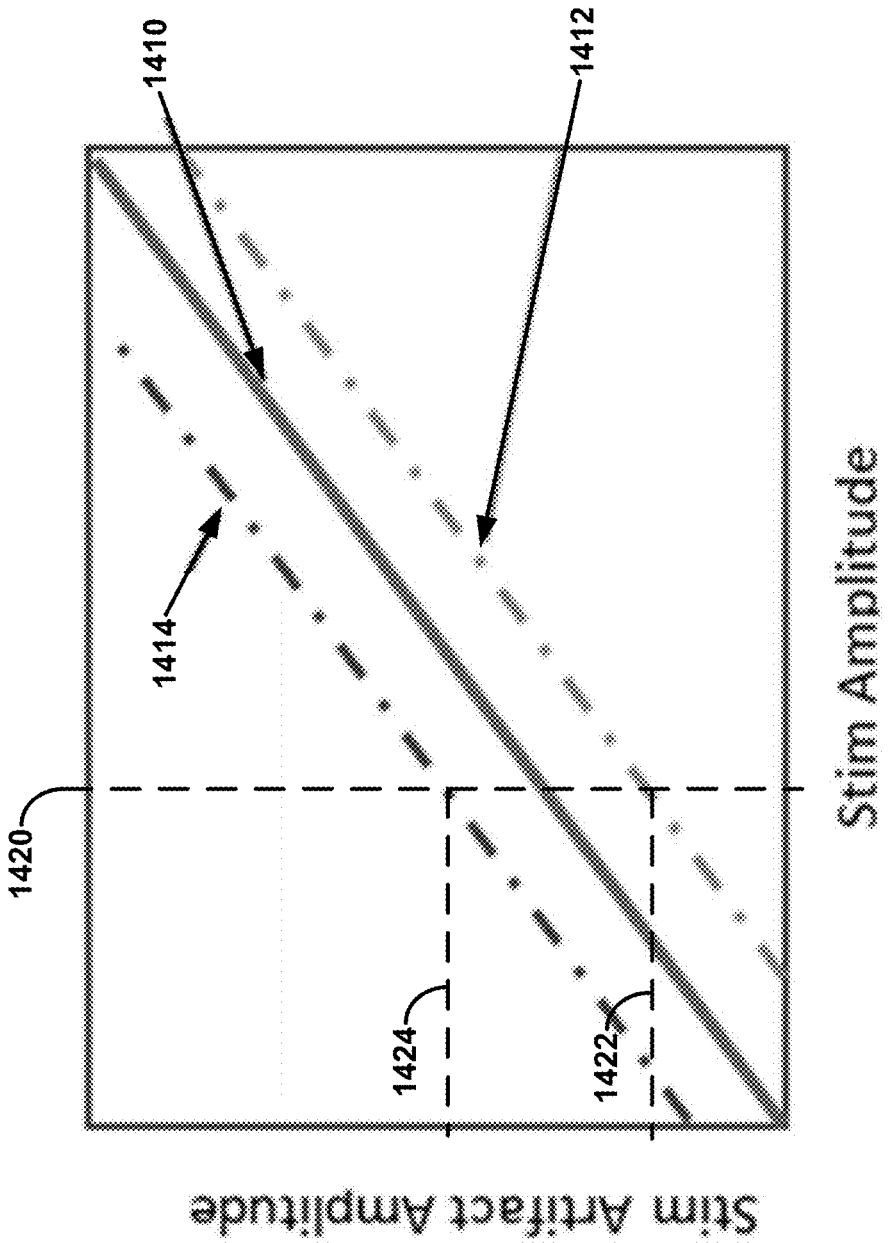

1410
1412
1414
1420
1424
1422
Stim Amplitude
Stim Artifact Amplitude

FIG. 14

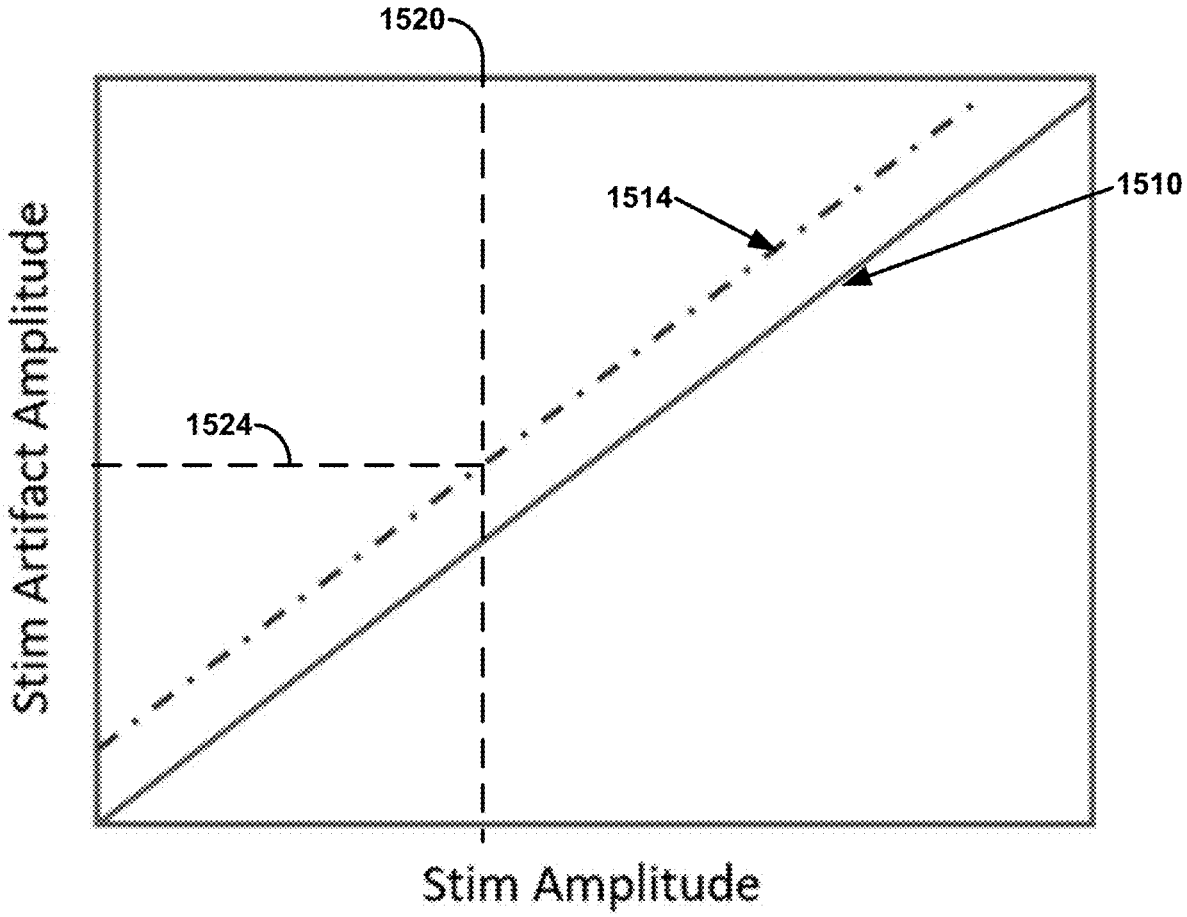

1520
1514
1510
1524
Stim Artifact Amplitude
Stim Amplitude

FIG. 15

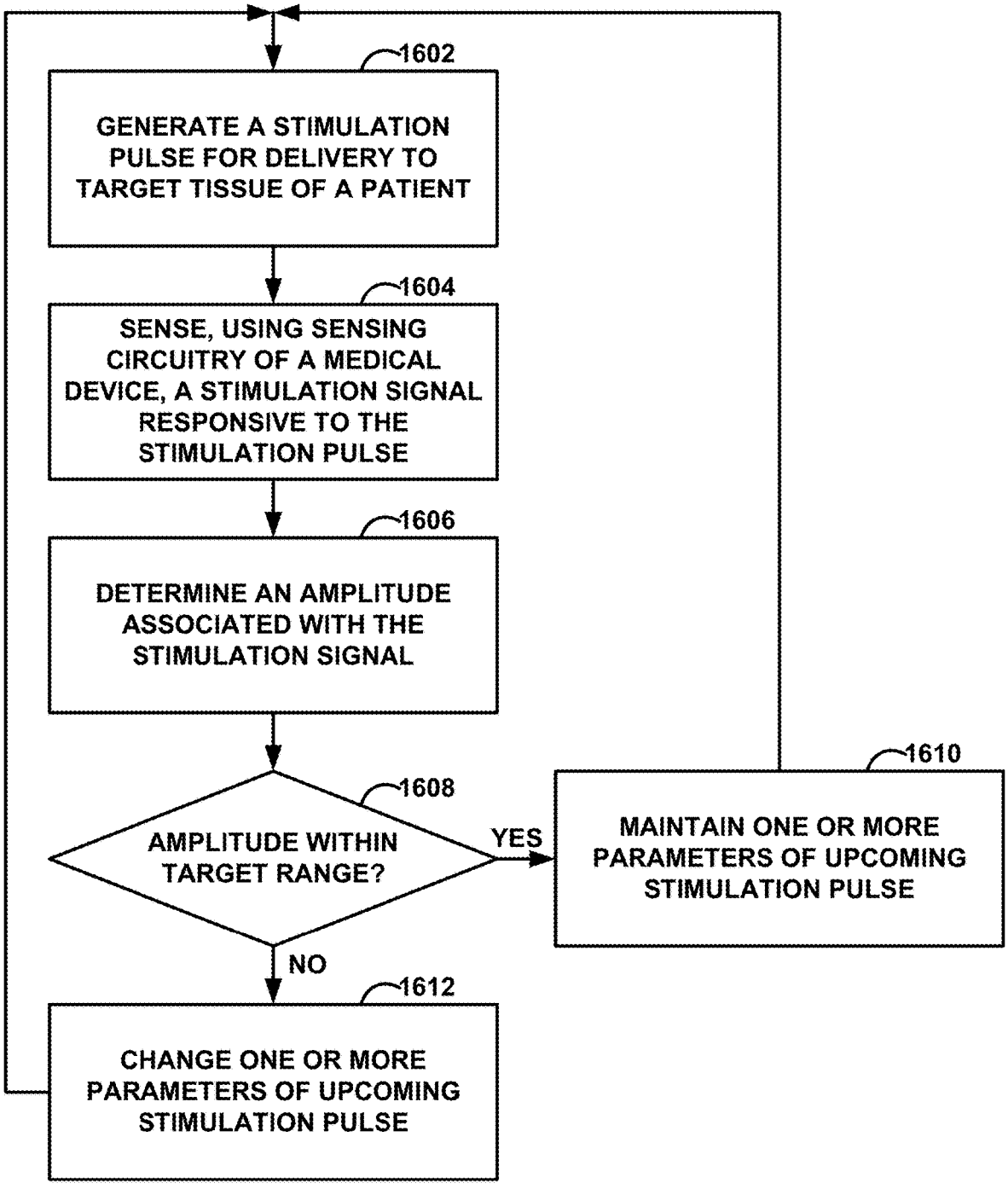

1602
GENERATE A STIMULATION PULSE FOR DELIVERY TO TARGET TISSUE OF A PATIENT
1604
SENSE, USING SENSING CIRCUITRY OF A MEDICAL DEVICE, A STIMULATION SIGNAL RESPONSIVE TO THE STIMULATION PULSE
1606
DETERMINE AN AMPLITUDE ASSOCIATED WITH THE STIMULATION SIGNAL
1608
AMPLITUDE WITHIN TARGET RANGE?
YES
NO
1610
MAINTAIN ONE OR MORE PARAMETERS OF UPCOMING STIMULATION PULSE
1612
CHANGE ONE OR MORE PARAMETERS OF UPCOMING STIMULATION PULSE

FIG. 16

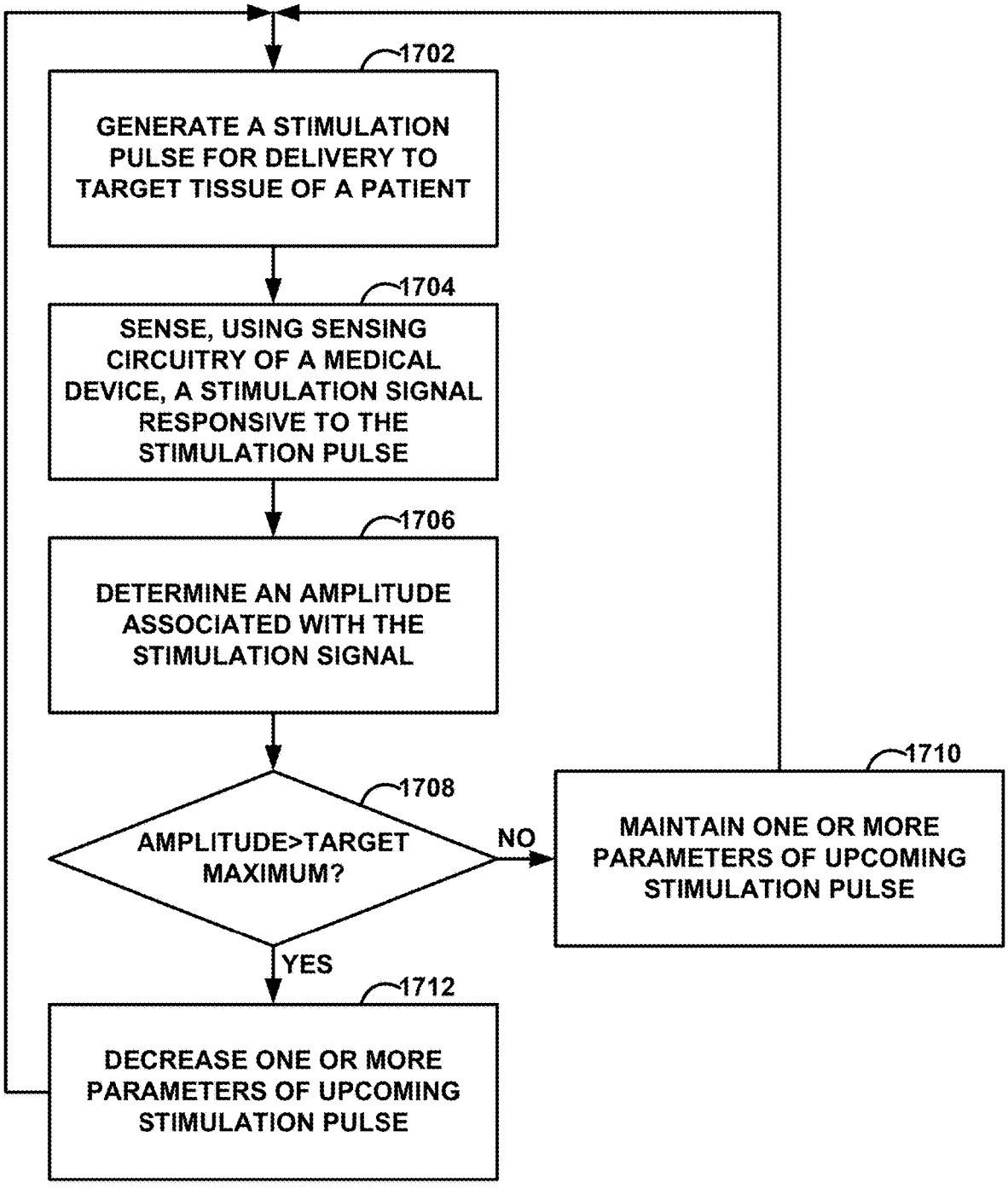

1702
GENERATE A STIMULATION PULSE FOR DELIVERY TO TARGET TISSUE OF A PATIENT
1704
SENSE, USING SENSING CIRCUITRY OF A MEDICAL DEVICE, A STIMULATION SIGNAL RESPONSIVE TO THE STIMULATION PULSE
1706
DETERMINE AN AMPLITUDE ASSOCIATED WITH THE STIMULATION SIGNAL
1708
AMPLITUDE>TARGET MAXIMUM?
NO
YES
1710
MAINTAIN ONE OR MORE PARAMETERS OF UPCOMING STIMULATION PULSE
1712
DECREASE ONE OR MORE PARAMETERS OF UPCOMING STIMULATION PULSE

FIG. 17

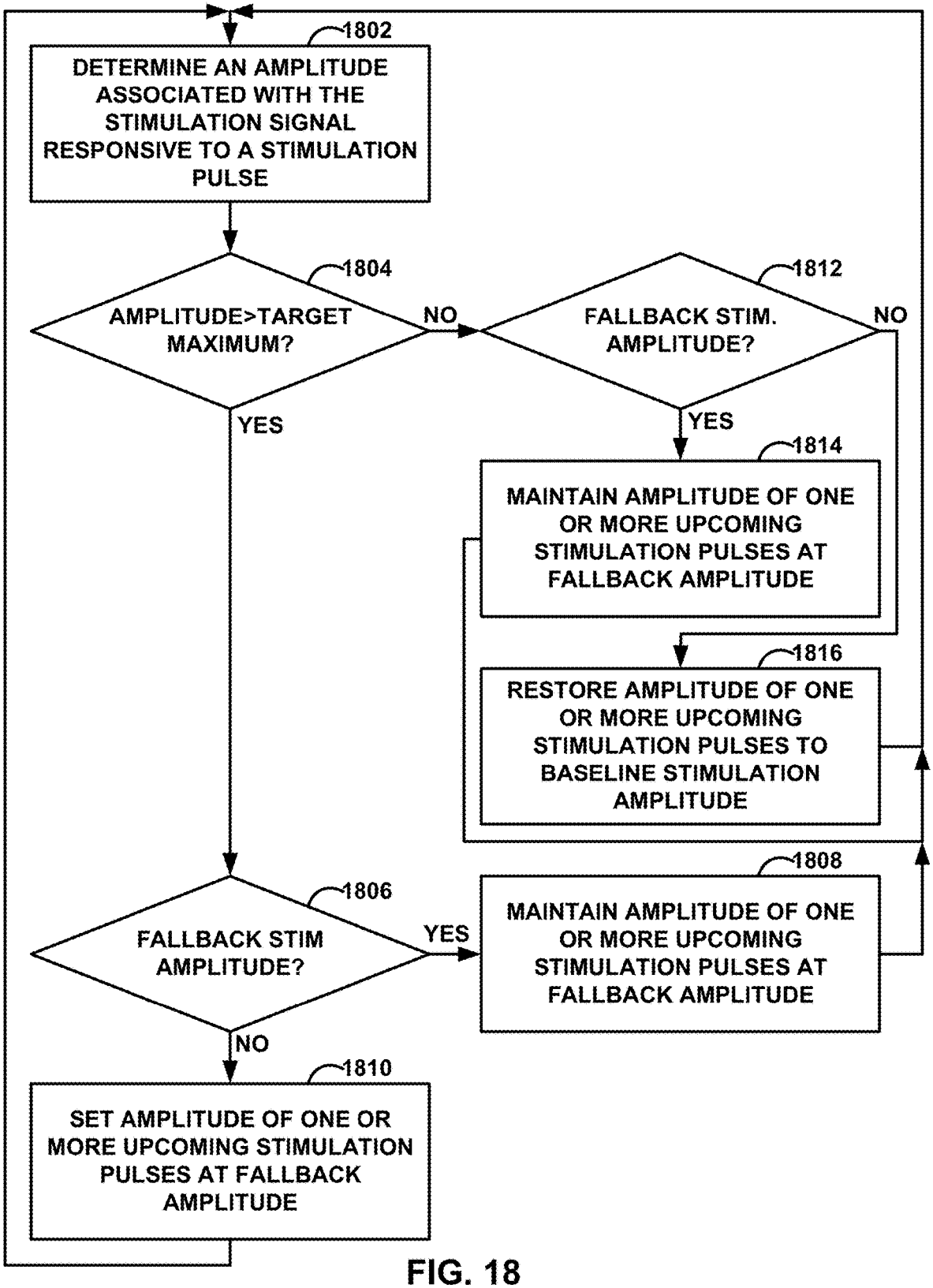

1802
DETERMINE AN AMPLITUDE ASSOCIATED WITH THE STIMULATION SIGNAL RESPONSIVE TO A STIMULATION PULSE
1804
AMPLITUDE>TARGET MAXIMUM?
NO
YES
1812
FALLBACK STIM. AMPLITUDE?
NO
YES
1814
MAINTAIN AMPLITUDE OF ONE OR MORE UPCOMING STIMULATION PULSES AT FALLBACK AMPLITUDE
1816
RESTORE AMPLITUDE OF ONE OR MORE UPCOMING STIMULATION PULSES TO BASELINE STIMULATION AMPLITUDE
1806
FALLBACK STIM AMPLITUDE?
YES
NO
1808
MAINTAIN AMPLITUDE OF ONE OR MORE UPCOMING STIMULATION PULSES AT FALLBACK AMPLITUDE
1810
SET AMPLITUDE OF ONE OR MORE UPCOMING STIMULATION PULSES AT FALLBACK AMPLITUDE

FIG. 18

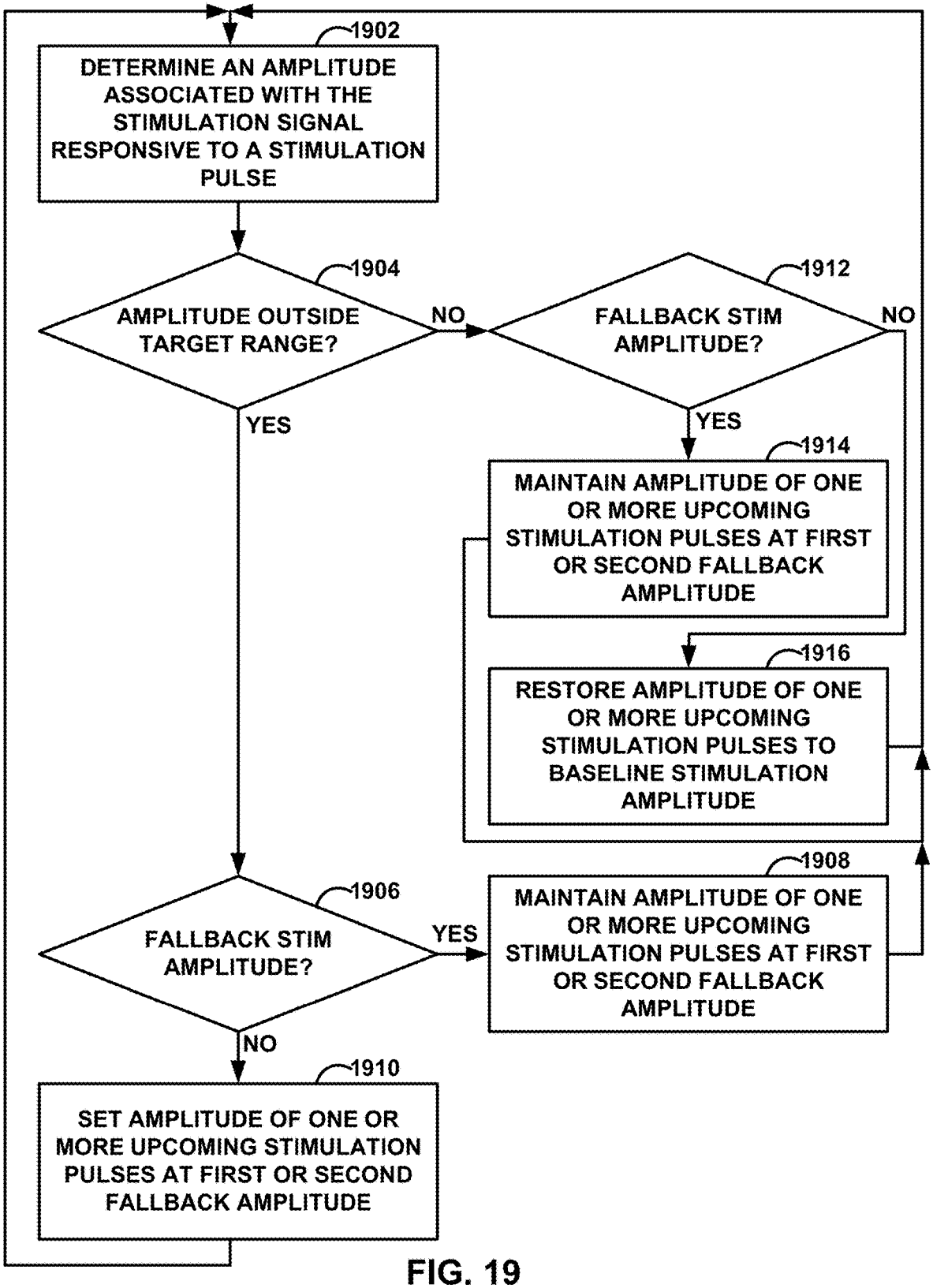

1902
DETERMINE AN AMPLITUDE ASSOCIATED WITH THE STIMULATION SIGNAL RESPONSIVE TO A STIMULATION PULSE
1904
AMPLITUDE OUTSIDE TARGET RANGE?
NO
YES
1912
FALLBACK STIM AMPLITUDE?
NO
YES
1914
MAINTAIN AMPLITUDE OF ONE OR MORE UPCOMING STIMULATION PULSES AT FIRST OR SECOND FALLBACK AMPLITUDE
1916
RESTORE AMPLITUDE OF ONE OR MORE UPCOMING STIMULATION PULSES TO BASELINE STIMULATION AMPLITUDE
1906
FALLBACK STIM AMPLITUDE?
YES
NO
1908
MAINTAIN AMPLITUDE OF ONE OR MORE UPCOMING STIMULATION PULSES AT FIRST OR SECOND FALLBACK AMPLITUDE
1910
SET AMPLITUDE OF ONE OR MORE UPCOMING STIMULATION PULSES AT FIRST OR SECOND FALLBACK AMPLITUDE

FIG. 19

CONTROLLING ELECTRICAL STIMULATION BASED ON A SENSED STIMULATION SIGNAL

This application claims the benefit of U.S. Provisional Patent Application No. 62/986,458, filed on Mar. 6, 2020, the entire content of which is incorporated herein by reference.

TECHNICAL FIELD

This disclosure generally relates to electrical stimulation therapy, and more specifically, control of electrical stimulation therapy.

BACKGROUND

Medical devices may be external or implanted and may be used to deliver electrical stimulation therapy to patients via various tissue sites to treat a variety of symptoms or conditions such as chronic pain, tremor, Parkinson's disease, epilepsy, urinary or fecal incontinence, sexual dysfunction, obesity, or gastroparesis. A medical device may deliver electrical stimulation therapy via one or more leads that include electrodes located proximate to target locations associated with the brain, the spinal cord, pelvic nerves, peripheral nerves, or the gastrointestinal tract of a patient. Stimulation proximate the spinal cord, proximate the sacral nerve, within the brain, and proximate peripheral nerves are often referred to as spinal cord stimulation (SCS), sacral neuromodulation (SNM), deep brain stimulation (DBS), and peripheral nerve stimulation (PNS), respectively.

SUMMARY

In general, the disclosure is directed to devices, systems, and techniques for controlling electrical stimulation therapy by sensing at least one of stimulation signals or evoked compound action potentials (ECAPs). A medical device (e.g., an implantable medical device) can deliver one or more stimulation signals (e.g., one or more pulses) to the patient via one or more leads, and the medical device may sense respective stimulation signals and/or ECAPs elicited by the pulses. For example, the medical device may be configured to sense electrical signals. While sensing electrical signals, the medical device may sense one or more stimulation signals that are indicative of the delivered pulse. The medical device may also sense an ECAP from the delivered pulse if the delivered pulse causes a sufficient number of nerve fibers to depolarize. In response to determining that a characteristic of one or more stimulation signals (e.g., a voltage amplitude) have deviated from a target stimulation signal characteristic value, the medical device may adjust a value of one or more stimulation parameters that define a subsequent (e.g., a next) stimulation pulse to be delivered to the patient. For example, the medical device may increase or decrease a current amplitude of the next pulse(s) by a predetermined step size or based on a gain value representative of an amount of deviation from the target stimulation signal characteristic value. In this manner, the medical device may be configured to maintain a consistent volume of neural activation by adjusting the value of one or more stimulation parameters that at least partially define stimulation pulses.

In some examples, a medical device includes stimulation generation circuitry configured to deliver a first stimulation pulse to a patient; sensing circuitry configured to sense the first stimulation pulse; and processing circuitry configured to: determine that a value of a characteristic of the sensed first stimulation pulse exceeds a target stimulation pulse value; and responsive to determining that the value of the characteristic of the sensed first stimulation pulse exceeds the target stimulation pulse value, change a first value of a parameter to a second value of the parameter that at least partially defines a second stimulation pulse deliverable by the stimulation generation circuitry after the first stimulation pulse was sensed.

In some examples, a method includes delivering, by stimulation generation circuitry, a first stimulation pulse to a patient; sensing, by sensing circuitry, the first stimulation pulse; determining, by processing circuitry, that a value of a characteristic of the sensed first stimulation pulse exceeds a target stimulation pulse value; and responsive to determining that the value of the characteristic of the sensed first stimulation pulse exceeds the target stimulation pulse value, changing, by the processing circuitry, a first value of a parameter to a second value of the parameter that at least partially defines a second stimulation pulse deliverable by the stimulation generation circuitry after the first stimulation pulse was sensed.

In some examples, a medical device includes stimulation generation circuitry configured to deliver a first stimulation pulse to a patient; sensing circuitry configured to sense a residual phase of the first stimulation pulse; and processing circuitry configured to: determine that a value of a characteristic of the sensed residual phase of the first stimulation pulse exceeds a target residual phase value; and responsive to determining that the value of the characteristic of the sensed residual phase exceeds the target residual phase value, change a first value of a parameter to a second value of the parameter that at least partially defines a second stimulation pulse deliverable by the stimulation generation circuitry after the residual phase of the first stimulation pulse was sensed.

The summary is intended to provide an overview of the subject matter described in this disclosure. It is not intended to provide an exclusive or exhaustive explanation of the systems, device, and methods described in detail within the accompanying drawings and description below. Further details of one or more examples of this disclosure are set forth in the accompanying drawings and in the description below. Other features, objects, and advantages will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a conceptual diagram illustrating an example system that includes an implantable medical device (IMD) configured to deliver spinal cord stimulation (SCS) therapy and an external programmer, in accordance with one or more techniques of this disclosure.

FIG. **2** is a block diagram illustrating an example configuration of components of the IMD of FIG. **1**, in accordance with one or more techniques of this disclosure.

FIG. **3** is a block diagram illustrating an example configuration of components of the external programmer of FIG. **1**, in accordance with one or more techniques of this disclosure.

FIG. **4** is a graph **402** of example evoked compound action potentials (ECAPs) sensed for respective stimulation pulses, in accordance with one or more techniques of this disclosure.

FIG. **5**A is an example timing diagram illustrating an example of electrical stimulation pulses, respective stimu-

lation signals, and respective sensed ECAPs, in accordance with one or more techniques of this disclosure.

FIG. **5**B is another example timing diagram illustrating an example of electrical stimulation pulses, respective stimulation signals, and respective sensed ECAPs, in accordance with one or more techniques of this disclosure.

FIG. **6**A is another example timing diagram illustrating an example of electrical stimulation pulses, respective stimulation signals, and respective sensed ECAPs, in accordance with one or more techniques of this disclosure.

FIG. **6**B is another example timing diagram illustrating one example of electrical stimulation pulses, respective stimulation signals, and respective sensed ECAPs, in accordance with one or more techniques of this disclosure.

FIG. **7** is another example timing diagram illustrating an example of electrical stimulation pulses, respective stimulation signals, and respective ECAPs, in accordance with one or more techniques of this disclosure.

FIG. **8** is another example timing diagram illustrating an example of electrical stimulation pulses, respective stimulation signals, and respective ECAPs, in accordance with one or more techniques of this disclosure.

FIG. **9** is a graph illustrating a stimulation pulse amplitude plot and a stimulation signal amplitude plot, in accordance with one or more techniques of this disclosure.

FIG. **10** is a graph illustrating a stimulation signal amplitude plot and an ECAP amplitude plot, in accordance with one or more techniques of this disclosure.

FIG. **11** is a timing diagram illustrating an example of an electrical stimulation pulse and a respective stimulation signal, in accordance with one or more techniques of this disclosure.

FIG. **12** is a timing diagram illustrating an example of an electrical stimulation pulse, a respective ECAP, and a respective stimulation signal, in accordance with one or more techniques of this disclosure.

FIG. **13** is a graph illustrating a first transfer function corresponding to a first posture, a second transfer function corresponding to a second posture, and a third transfer function corresponding to a third posture, in accordance with one or more techniques of this disclosure.

FIG. **14** is a graph illustrating a target range of amplitude values for a stimulation signal in relation to a transfer function corresponding to a respective patient posture, in accordance with one or more techniques of this disclosure.

FIG. **15** is a graph illustrating target maximum values for a stimulation signal in relation to a transfer function corresponding to a respective patient posture, in accordance with one or more techniques of this disclosure.

FIG. **16** is a flow diagram illustrating an example operation for controlling simulation based on one or more stimulation signals, in accordance with one or more techniques of this disclosure.

FIG. **17** is a flow diagram illustrating another example operation for controlling simulation based on one or more stimulation signals, in accordance with one or more techniques of this disclosure.

FIG. **18** is a flow diagram illustrating another example operation for controlling simulation based on one or more stimulation signals, in accordance with one or more techniques of this disclosure.

FIG. **19** is a flow diagram illustrating another example operation for controlling simulation based on one or more stimulation signals, in accordance with one or more techniques of this disclosure.

Like reference characters denote like elements throughout the description and figures.

DETAILED DESCRIPTION

The disclosure describes examples of medical devices, systems, and techniques for automatically adjusting electrical stimulation therapy delivered to a patient based on a characteristic of one or more stimulation signals sensed by a medical device in response to stimulation pulses (e.g., control pulses and/or informed pulses) delivered by the medical device and, in some examples, characteristics of evoked compound action potentials (ECAPs) detected by a medical device. Electrical stimulation therapy is typically delivered to a target tissue (e.g., one or more nerves or muscle) of a patient via two or more electrodes. Parameters of the electrical stimulation therapy (e.g., electrode combination, voltage or current amplitude, pulse width, pulse frequency, etc.) are selected by a clinician and/or the patient to provide relief from various symptoms, such as pain, muscle disorders, etc. However, as the patient moves, the distance between the electrodes and the target tissues changes. Since neural recruitment is a function of stimulation intensity and distance between the target tissue and the electrodes, movement of the electrode closer to the target tissue may result in increased perception by the patient (e.g., possible painful sensations), and movement of the electrode further from the target tissue may result in decreased efficacy of the therapy for the patient.

ECAPs are a measure of neural recruitment because each ECAP signal represents the superposition of electrical potentials generated from axons firing in response to an electrical stimulus (e.g., a stimulation pulse). Changes in a characteristic (e.g., an amplitude of a portion of the signal, an area under one or more peaks, frequency content, and/or maximum and/or minimum peak timing) of an ECAP signal occur as a function of how many axons have been activated by the delivered stimulation pulse. A system can monitor changes in the characteristic of the ECAP signal and use that change in the characteristic to adjust one or more stimulation parameters that at least partially defines the stimulation pulses delivered to the patient. For example, the system can reduce the intensity of stimulation pulses (e.g., reduce a current amplitude and/or pulse width) in response to detecting an increase in an amplitude of an ECAP signal.

Nerve impulses may be detectable as the ECAP signal travels quickly along the nerve fiber after the delivered stimulation pulse first depolarizes the nerve. Therefore, if the stimulation pulse delivered by first electrodes has a pulse width that is too long, different electrodes configured to sense the ECAP will sense the stimulation pulse itself as a stimulation signal that obscures the lower amplitude ECAP signal. However, the ECAP signal loses fidelity as the electrical potentials propagate from the electrical stimulus because different nerve fibers propagate electrical potentials at different speeds. Therefore, sensing the ECAP at a far distance from the stimulating electrodes may avoid the stimulation signal caused by a stimulation pulse with a long pulse width, but the ECAP signal may lose fidelity needed to detect changes to the ECAP signal that occur when the electrode to target tissue distance changes or when a targeted activated fiber distribution changes or terminates before a sensing electrode location. In other words, the system may not be able to identify, at any distance from the stimulation electrodes, ECAPs from stimulation pulses configured to provide a therapy to the patient.

Although a system can use ECAP signals to detect changes to stimulation therapy, ECAP signals may not always be present or detectable. For example, the delivered stimulation pulse may have an intensity that is too low to

elicit a detectable ECAP signal. For example, the stimulation pulse may be referred to as a "sub-threshold" stimulation pulse because the stimulation pulse is below at least one of a perception threshold, a motor threshold, or an ECAP detection threshold. Sub-threshold stimulation pulses may cause a therapeutic effect for the patient, but the lack of a detectable ECAP signal may prevent the system from using an ECAP signal to modulate stimulation parameter values in response to changes in the distance between electrodes and target tissue (e.g., target nerves).

A medical device may be configured to sense stimulation signals and adjust stimulation parameters based on a characteristic of one or more stimulation signals. As discussed above, ECAPs elicited by stimulation pulses delivered by the medical device might not be detectible by the medical device. Even if an ECAP signal is not detectable, the medical device may detect one or more stimulation signals caused by the stimulation pulse. The medical device may determine or adjust values of one or more parameters that at least partially define subsequent stimulation pulses based characteristic of the respective stimulation signals. More specifically, the stimulation signals detected by the medical device may include information indicative of an efficacy of therapy delivered to the patient by the medical device. For example, the stimulation signals may include information indicative of a distance between one or more electrodes of the medical device and the target tissue. In this way, the medical device may adjust stimulation therapy according to the characteristics of one or more stimulation signals in order to maintain efficacy of the therapy and/or reduce undesirable side effects during or as a result of patient movement.

The term "stimulation signal" may be used herein to describe a signal that the medical device senses in response to a stimulation pulse delivered by the medical device. One or more sense electrodes of the medical device may detect a stimulation signal due to one or more stimulation electrodes proximate to the sense electrodes delivering a stimulation pulse. In this way, delivering a stimulation pulse may cause the medical device to sense a respective stimulation signal during a window of time substantially overlapping with the delivery of the stimulation pulse. An electrical potential of the stimulation electrodes during the window of time in which the medical device delivers the stimulation pulse may cause the sensing circuitry of the medical device to generate a sense signal which is representative of the stimulation pulse delivered during the window of time. The stimulation signal is thus representative of electrical potential changes in tissue directly caused by the delivered stimulation pulse. Conversely, an ECAP is a signal representative of physiological action (e.g., depolarizing nerve fibers) caused by the stimulation pulse. In this way, stimulation signals may be at least partially distinguished from ECAPs, since ECAPs represent electrical signals sensed by the medical device due to an excitation of target tissue of the patient in response to the delivery of a stimulation pulse. In other words, an ECAP represents a detected physiological response to a stimulation pulse, and a stimulation signal represents the direct detection of the stimulation pulse itself and associated changes in the charge in tissue.

In some examples, the medical device may deliver stimulation pulses in the form of control pulses and informed pulses. More specifically, electrical stimulation pulses are delivered in the form of informed pulses and control pulses that are at least partially interleaved with each other. Control pulses (e.g., stimulation signal test pulses) are those stimulation pulses that are configured to elicit one or both of a stimulation signal and a detectable ECAP signal. In some examples, control pulses may contribute to the therapy for a patient. In other examples, control pulses do not contribute to the therapy for the patient, e.g., non-therapeutic pulses. In this manner, control pulses may or may not be configured to elicit a therapeutic effect for the patient. Informed pulses are those stimulation pulses that are at least partially defined by one or more parameters based on the detectable stimulation signal elicited from one or more control pulses. In some examples, one or more informed pulses are at least partially defined by one or more parameters based on a respective ECAP elicited from one or more control pulses. In this manner, the informed pulses are "informed" by the ECAP signal detected from a control pulse. Informed pulses are also configured to provide a therapy to a patient, such as paresthesia that relieves pain symptoms.

As described herein, a medical device may be configured to deliver a plurality of informed pulses and/or control pulses configured to provide a therapy to the patient based on one or more parameters of ECAP signals elicited by previously delivered control pulses. The medical device, in some cases, may deliver a plurality of informed pulses, which are configured to provide or at least contribute to a therapy to the patient based on one or more parameters of ECAP signals elicited by control pulses. In some examples, the control pulses may be configured to elicit ECAP signals without contributing to the therapy of the patient. However, in other examples, the control pulses may provide therapy to the patient either alone or in combination with the informed pulses. The control pulses may be interleaved with the delivery of the informed pulses. For example, the medical device may alternate the delivery of informed pulses with control pulses such that a control pulse is delivered, and an ECAP signal is sensed from the control pulses, between consecutive informed pulses. In some examples, multiple control pulses are delivered, and respective ECAP signals sensed, between the delivery of consecutive informed pulses.

In some examples, multiple informed pulses will be delivered between consecutive control pulses. In any case, the informed pulses may be delivered according to a predetermined pulse frequency selected so that the informed pulses can produce or contribute to a therapeutic result for the patient. One or more control pulses are then delivered, and the respective ECAP signals sensed, within one or more time windows between consecutive informed pulses delivered according to the predetermined pulse frequency. The predetermined pulse frequency may be a single consistent frequency or a varied frequency that varies over time. The pulse width of the control pulses may be shorter than the pulse width of the informed pulses to enable the medical device to detect the stimulation signals and/or the ECAP signals elicited from the control pulses. Put another way, the longer pulse width of the informed pulses may prevent all phases of the resulting stimulation signals and prevent the resulting ECAP signals from being detected due to, for example, overlapping of the informed pulse with the ECAP signal and the stimulation signal. In this manner, a medical device can administer informed pulses from the medical device uninterrupted while one or both of ECAPs and stimulation signals can be sensed from control pulses delivered during times at which the informed pulses are not being delivered.

In some examples, a pulse frequency of stimulation pulses (e.g., control pulses and informed pules) delivered by the medical device may be within a range from 50 Hertz (Hz) to 70 Hz, but this is not required. In some examples, a pulse

frequency of stimulation pulses (e.g., control pulses and informed pules) delivered by the medical device may be within a range from 0.1 Hz to 100 kilohertz (KHz), The pulse frequency of the stimulation pulses may be within a range from 0.5 KHz to 5 KHz (e.g., 1 KHz) and/or within a range from 5 KHz to 15 KHz (e.g., 10 KHz), as examples. In some examples, when a frequency of control pulses and informed pulses increases, a maximum pulse width of control pulses which do not obscure respective control pulses decreases.

The medical device may, in some cases, determine whether a characteristic of a stimulation signal detected in response to a stimulation pulse (e.g., a control pulse) is within a range from a first threshold characteristic value to a second threshold characteristic value. The first threshold characteristic value and the second threshold characteristic value which define the range may, in some cases, depend on a posture of the patient and a magnitude of the stimulation pulse which provokes the stimulation signal sensed by the medical device. The medical device may determine the posture of the patient using an accelerometer signal. In this way, the medical device may determine one or more parameters of stimulation delivered to the patient based on whether the characteristic of the stimulation signal is within the respective range of stimulation signal characteristic values, where the range is determined based on the posture of the patient and the magnitude of the stimulation pulses (e.g., voltage magnitude, current magnitude).

Although electrical stimulation is generally described herein in the form of electrical stimulation pulses, electrical stimulation may be delivered in non-pulse form in other examples. For example, electrical stimulation may be delivered as a signal having various waveform shapes, frequencies, and amplitudes. Therefore, electrical stimulation in the form of a non-pulse signal may be a continuous signal than may have a sinusoidal waveform or other continuous waveform.

The techniques of this disclosure may provide one or more advantages. For example, a medical device may control stimulation based on one or more stimulation signals when an ECAP is not elicited by the delivered pulse or the ECAP is otherwise not detectable. In this way, the medical device may determine a value for one or more parameters that define stimulation pulses based on a characteristic value of the one or more stimulation signals detected from previous stimulation pulse. In one example, the value for one or more parameters of the stimulation pulses may be determined from a characteristic of a third phase or residual phase of the stimulation signal (e.g., one of the stimulation signals) detected from a stimulation pulse. The third phase may occur within the final third of the stimulation signal, and the third phase may be referred to as a residual phase because it represents ionic rebalancing of any residual charge resulting from the stimulation pulse that was delivered. In this way, the medical device may be configured to determine therapy based on one or more stimulation signals when an ECAP is not present or is otherwise not detectible by the medical device. Additionally, the medical device may adjust stimulation parameters for subsequent pulses based on a characteristic value of a stimulation signal and a characteristic of an ECAP elicited by the same pulse that caused the stimulation signal. In this manner, the stimulation signal may improve the quality of feedback signals available for controlling stimulation even if the ECAP signal is detectable.

FIG. **1** is a conceptual diagram illustrating an example system **100** that includes an implantable medical device (IMD) **110** configured to deliver spinal cord stimulation (SCS) therapy and an external programmer **150**, in accordance with one or more techniques of this disclosure. Although the techniques described in this disclosure are generally applicable to a variety of medical devices including external devices and IMDs, application of such techniques to IMDs and, more particularly, implantable electrical stimulators (e.g., neurostimulators) will be described for purposes of illustration. More particularly, the disclosure will refer to an implantable SCS system for purposes of illustration, but without limitation as to other types of medical devices or other therapeutic applications of medical devices.

As shown in FIG. **1**, system **100** includes an IMD **110**, leads **130**A and **130**B, and external programmer **150** shown in conjunction with a patient **105**, who is ordinarily a human patient. In the example of FIG. **1**, IMD **110** is an implantable electrical stimulator that is configured to generate and deliver electrical stimulation therapy to patient **105** via one or more electrodes of electrodes of leads **130**A and/or **130**B (collectively, "leads **130**"), e.g., for relief of chronic pain or other symptoms. In other examples, IMD **110** may be coupled to a single lead carrying multiple electrodes or more than two leads each carrying multiple electrodes. This electrical stimulation may be delivered in the form of stimulation pulses. In some examples, IMD **110** may be configured to generate and deliver stimulation pulses to include control pulses configured to elicit ECAP signals and/or cause IMD **110** to sense stimulation signals. The control pulses may or may not contribute to therapy in some examples. In some examples, IMD **110** may, in addition to control pulses, deliver informed pulses that contribute to the therapy for the patient, but which do not elicit detectable ECAPs or cause IMD **110** to detect every phase of responsive stimulation signals. IMD **110** may be a chronic electrical stimulator that remains implanted within patient **105** for weeks, months, or even years. In other examples, IMD **110** may be a temporary, or trial, stimulator used to screen or evaluate the efficacy of electrical stimulation for chronic therapy. In one example, IMD **110** is implanted within patient **105**, while in another example, IMD **110** is an external device coupled to percutaneously implanted leads. In some examples, IMD **110** uses one or more leads, while in other examples, IMD **110** is leadless.

IMD **110** may be constructed of any polymer, metal, or composite material sufficient to house the components of IMD **110** (e.g., components illustrated in FIG. **2**) within patient **105**. In this example, IMD **110** may be constructed with a biocompatible housing, such as titanium or stainless steel, or a polymeric material such as silicone, polyurethane, or a liquid crystal polymer, and surgically implanted at a site in patient **105** near the pelvis, abdomen, or buttocks. In other examples, IMD **110** may be implanted within other suitable sites within patient **105**, which may depend, for example, on the target site within patient **105** for the delivery of electrical stimulation therapy. The outer housing of IMD **110** may be configured to provide a hermetic seal for components, such as a rechargeable or non-rechargeable power source. In addition, in some examples, the outer housing of IMD **110** is selected from a material that facilitates receiving energy to charge the rechargeable power source.

Electrical stimulation energy, which may be constant current or constant voltage-based pulses, for example, is delivered from IMD **110** to one or more target tissue sites of patient **105** via one or more electrodes (not shown) of implantable leads **130**. In the example of FIG. **1**, leads **130** carry electrodes that are placed adjacent to the target tissue of spinal cord **120**. One or more of the electrodes may be

disposed at a distal tip of a leads **130** and/or at other positions at intermediate points along the lead. Leads **130** may be implanted and coupled to IMD **110**. The electrodes may transfer electrical stimulation generated by an electrical stimulation generator in IMD **110** to tissue of patient **105**. Although leads **130** may each be a single lead, leads **130** may include a lead extension or other segments that may aid in implantation or positioning of leads **130**. In some other examples, IMD **110** may be a leadless stimulator with one or more arrays of electrodes arranged on a housing of the stimulator rather than leads that extend from the housing. In addition, in some other examples, system **100** may include one lead or more than two leads, each coupled to IMD **110** and directed to similar or different target tissue sites.

The electrodes of leads **130** may be electrode pads on a paddle lead, circular (e.g., ring) electrodes surrounding the body of the lead, conformable electrodes, cuff electrodes, segmented electrodes (e.g., electrodes disposed at different circumferential positions around the lead instead of a continuous ring electrode), any combination thereof (e.g., ring electrodes and segmented electrodes) or any other type of electrodes capable of forming unipolar, bipolar or multipolar electrode combinations for therapy. Ring electrodes arranged at different axial positions at the distal ends of lead **130** will be described for purposes of illustration.

The deployment of electrodes via leads **130** is described for purposes of illustration, but arrays of electrodes may be deployed in different ways. For example, a housing associated with a leadless stimulator may carry arrays of electrodes, e.g., rows and/or columns (or other patterns), to which shifting operations may be applied. Such electrodes may be arranged as surface electrodes, ring electrodes, or protrusions. As a further alternative, electrode arrays may be formed by rows and/or columns of electrodes on one or more paddle leads. In some examples, electrode arrays include electrode segments, which are arranged at respective positions around a periphery of a lead, e.g., arranged in the form of one or more segmented rings around a circumference of a cylindrical lead. In other examples, one or more of leads **130** are linear leads having 8 ring electrodes along the axial length of the lead. In another example, the electrodes are segmented rings arranged in a linear fashion along the axial length of the lead and at the periphery of the lead.

The stimulation parameter of a therapy stimulation program that defines the stimulation pulses of electrical stimulation therapy by IMD **110** through the electrodes of leads **130** may include information identifying which electrodes have been selected for delivery of stimulation according to a stimulation program, the polarities of the selected electrodes, i.e., the electrode combination for the program, and voltage or current amplitude, pulse frequency, pulse width, pulse shape of stimulation delivered by the electrodes. These stimulation parameters of stimulation pulses (e.g., control pulses and/or informed pulses) are typically predetermined parameter values determined prior to delivery of the stimulation pulses (e.g., set according to a stimulation program). However, in some examples, system **100** changes one or more parameter values automatically based on one or more factors or based on user input.

A test stimulation program may define stimulation parameter values that define control pulses delivered by IMD **110** through at least some of the electrodes of leads **130**. These stimulation parameter values may include information identifying which electrodes have been selected for delivery of control pulses, the polarities of the selected electrodes, i.e., the electrode combination for the program, and voltage or current amplitude, pulse frequency, pulse width, and pulse shape of stimulation delivered by the electrodes. The stimulation signals (e.g., one or more stimulation pulses or a continuous stimulation waveform) defined by the parameters of each test stimulation program are configured to evoke a compound action potential from nerves. In some examples, the test stimulation program defines when the control pulses are to be delivered to the patient based on the frequency and/or pulse width of the informed pulses when informed pulse are also delivered. In some examples, the stimulation defined by each test stimulation program are not intended to provide or contribute to therapy for the patient. In other examples, the stimulation defined by each test stimulation program may contribute to therapy when the control pulses elicit one or both of detectable ECAP signals and detect responsive stimulation signals. In this manner, the test stimulation program may define stimulation parameters the same or similar to the stimulation parameters of therapy stimulation programs.

Although FIG. **1** is directed to SCS therapy, e.g., used to treat pain, in other examples system **100** may be configured to treat any other condition that may benefit from electrical stimulation therapy. For example, system **100** may be used to treat tremor, Parkinson's disease, epilepsy, a pelvic floor disorder (e.g., urinary incontinence or other bladder dysfunction, fecal incontinence, pelvic pain, bowel dysfunction, or sexual dysfunction), obesity, gastroparesis, or psychiatric disorders (e.g., depression, mania, obsessive compulsive disorder, anxiety disorders, and the like). In this manner, system **100** may be configured to provide therapy taking the form of deep brain stimulation (DBS), peripheral nerve stimulation (PNS), peripheral nerve field stimulation (PNFS), cortical stimulation (CS), pelvic floor stimulation, gastrointestinal stimulation, or any other stimulation therapy capable of treating a condition of patient **105**.

In some examples, leads **130** includes one or more sensors configured to allow IMD **110** to monitor one or more parameters of patient **105**, such as patient activity, pressure, temperature, or other characteristics. The one or more sensors may be provided in addition to, or in place of, therapy delivery by leads **130**.

IMD **110** is configured to deliver electrical stimulation therapy to patient **105** via selected combinations of electrodes carried by one or both of leads **130**, alone or in combination with an electrode carried by or defined by an outer housing of IMD **110**. The target tissue for the electrical stimulation therapy may be any tissue affected by electrical stimulation, which may be in the form of electrical stimulation pulses or continuous waveforms. In some examples, the target tissue includes nerves, smooth muscle or skeletal muscle. In the example illustrated by FIG. **1**, the target tissue is tissue proximate spinal cord **120**, such as within an intrathecal space or epidural space of spinal cord **120**, or, in some examples, adjacent nerves that branch off spinal cord **120**. Leads **130** may be introduced into spinal cord **120** in via any suitable region, such as the thoracic, cervical or lumbar regions. Stimulation of spinal cord **120** may, for example, prevent pain signals from traveling through spinal cord **120** and to the brain of patient **105**. Patient **105** may perceive the interruption of pain signals as a reduction in pain and, therefore, efficacious therapy results. In other examples, stimulation of spinal cord **120** may produce paresthesia which may be reduce the perception of pain by patient **105**, and thus, provide efficacious therapy results.

IMD **110** generates and delivers electrical stimulation therapy to a target stimulation site within patient **105** via the electrodes of leads **130** to patient **105** according to one or more therapy stimulation programs. A therapy stimulation

program defines values for one or more parameters that define an aspect of the therapy delivered by IMD **110** according to that program. For example, a therapy stimulation program that controls delivery of stimulation by IMD **110** in the form of pulses may define values for voltage or current pulse amplitude, pulse width, and pulse rate (e.g., pulse frequency) for stimulation pulses delivered by IMD **110** according to that program.

In some examples where relevant phases of stimulation signals cannot be detected from the types of pulses intended to be delivered to provide therapy to the patient, control pulses and informed pulses may be delivered. For example, IMD **110** is configured to deliver control stimulation to patient **105** via a combination of electrodes of leads **130**, alone or in combination with an electrode carried by or defined by an outer housing of IMD **110**. The tissue targeted by the control stimulation may be the same tissue targeted by the electrical stimulation therapy, but IMD **110** may deliver control stimulation pulses via the same, at least some of the same, or different electrodes. Since control stimulation pulses are delivered in an interleaved manner with informed pulses, a clinician and/or user may select any desired electrode combination for informed pulses. Like the electrical stimulation therapy, the control stimulation may be in the form of electrical stimulation pulses or continuous waveforms.

In one example, each control stimulation pulse may include a balanced, bi-phasic square pulse that employs an active recharge phase. However, in other examples, the control stimulation pulses may include a monophasic pulse followed by a passive recharge phase. In other examples, a control pulse may include an imbalanced bi-phasic portion and a passive recharge portion. In other examples, a control stimulation pulse may include a tri-phasic pulse or pulse having more than three phases. Although not necessary, a bi-phasic control pulse may include an interphase interval between the positive and negative phase to promote propagation of the nerve impulse in response to the first phase of the bi-phasic pulse. The control stimulation may be delivered without interrupting the delivery of the electrical stimulation informed pulses, such as during the window between consecutive informed pulses. In some cases, the control pulses may elicit an ECAP signal from the tissue, and IMD **110** may sense the ECAP signal via two or more electrodes on leads **130**. In some examples, control pulses might not elicit ECAPs that are detectible by IMD **110**, however IMD **110** may detect stimulation signals responsive to the control pulses. The control pulses may include information that is useful for determining parameters of one or more stimulation delivered to patient **105**. In cases where the control stimulation pulses are applied to spinal cord **120**, the signal may be sensed by IMD **110** from spinal cord **120**.

IMD **110** may deliver control stimulation to a target stimulation site within patient **105** via the electrodes of leads **130** according to one or more test stimulation programs. The one or more test stimulation programs may be stored in a storage device of IMD **110**. Each test program of the one or more test stimulation programs includes values for one or more parameters that define an aspect of the control stimulation delivered by IMD **110** according to that program, such as current or voltage amplitude, pulse width, pulse frequency, electrode combination, and, in some examples, timing based on informed pulses to be delivered to patient **105**. In some examples, IMD **110** delivers control stimulation to patient **105** according to multiple test stimulation programs.

A user, such as a clinician or patient **105**, may interact with a user interface of an external programmer **150** to program IMD **110**. Programming of IMD **110** may refer generally to the generation and transfer of commands, programs, or other information to control the operation of IMD **110**. In this manner, IMD **110** may receive the transferred commands and programs from external programmer **150** to control electrical stimulation therapy (e.g., informed pulses) and control stimulation (e.g., control pulses). For example, external programmer **150** may transmit therapy stimulation programs, test stimulation programs, stimulation parameter adjustments, therapy stimulation program selections, test program selections, user input, or other information to control the operation of IMD **110**, e.g., by wireless telemetry or wired connection. As described herein, stimulation delivered to the patient may include control pulses, and, in some examples, stimulation may include control pulses and informed pulses.

In some cases, external programmer **150** may be characterized as a physician or clinician programmer if it is primarily intended for use by a physician or clinician. In other cases, external programmer **150** may be characterized as a patient programmer if it is primarily intended for use by a patient. A patient programmer may be generally accessible to patient **105** and, in many cases, may be a portable device that may accompany patient **105** throughout the patient's daily routine. For example, a patient programmer may receive input from patient **105** when the patient wishes to terminate or change electrical stimulation therapy. In general, a physician or clinician programmer may support selection and generation of programs by a clinician for use by IMD **110**, whereas a patient programmer may support adjustment and selection of such programs by a patient during ordinary use. In other examples, external programmer **150** may include, or be part of, an external charging device that recharges a power source of IMD **110**. In this manner, a user may program and charge IMD **110** using one device, or multiple devices.

As described herein, information may be transmitted between external programmer **150** and IMD **110**. Therefore, IMD **110** and external programmer **150** may communicate via wireless communication using any techniques known in the art. Examples of communication techniques may include, for example, radiofrequency (RF) telemetry and inductive coupling, but other techniques are also contemplated. In some examples, external programmer **150** includes a communication head that may be placed proximate to the patient's body near the IMD **110** implant site to improve the quality or security of communication between IMD **110** and external programmer **150**. Communication between external programmer **150** and IMD **110** may occur during power transmission or separate from power transmission.

In some examples, IMD **110**, in response to commands from external programmer **150**, delivers electrical stimulation therapy according to a plurality of therapy stimulation programs to a target tissue site of the spinal cord **120** of patient **105** via electrodes (not depicted) on leads **130**. In some examples, IMD **110** modifies therapy stimulation programs as therapy needs of patient **105** evolve over time. For example, the modification of the therapy stimulation programs may cause the adjustment of at least one parameter of the plurality of informed pulses. When patient **105** receives the same therapy for an extended period, the efficacy of the therapy may be reduced. In some cases, parameters of the plurality of informed pulses may be automatically updated.

Efficacy of electrical stimulation therapy may, in some cases, be indicated by one or more characteristics (e.g. an amplitude of or between one or more peaks or an area under the curve of one or more peaks) of an action potential that is evoked by a stimulation pulse delivered by IMD **110** (i.e., a characteristic of the ECAP signal). Additionally, or alternatively, efficacy of electrical stimulation therapy may be indicated by one or more characteristics (e.g., a voltage magnitude) of a stimulation signal that is sensed in response to the stimulation pulse delivered by IMD **110**. The stimulation signal may be indicative of the detection of the delivered stimulation pulse and related signals instead of action potentials evoked by the delivered stimulation pulse.

In one or more cases where stimulation pulses elicit detectible ECAPs, electrical stimulation therapy delivery by leads **130** of IMD **110** may cause neurons within the target tissue to evoke a compound action potential that travels up and down the target tissue (e.g., nerve fibers), eventually arriving at sensing electrodes of IMD **110**. Furthermore, control stimulation may also elicit at least one ECAP, and ECAPs responsive to control stimulation may also be a surrogate for the effectiveness of the therapy. The amount of action potentials (e.g., number of neurons propagating action potential signals) that are evoked may be based on the various parameters of electrical stimulation pulses such as amplitude, pulse width, frequency, pulse shape (e.g., slew rate at the beginning and/or end of the pulse), etc. The slew rate may define the rate of change of the voltage and/or current amplitude of the pulse at the beginning and/or end of each pulse or each phase within the pulse. For example, a very high slew rate indicates a steep or even near vertical edge of the pulse, and a low slew rate indicates a longer ramp up (or ramp down) in the amplitude of the pulse. In some examples, these parameters contribute to an intensity of the electrical stimulation. In addition, a characteristic of the ECAP signal (e.g., an amplitude) may change based on the distance between the stimulation electrodes and the nerves subject to the electrical field produced by the delivered control stimulation pulses.

In one or more cases where a stimulation pulse causes IMD **110** to sense one or more respective stimulation signals, one or more characteristics of the respective stimulation signal may indicate an efficacy of the electrical stimulation delivered to patient **105** by IMD **110**. For example, it may be beneficial for a voltage magnitude of the stimulation signal to be at a target stimulation signal value. In one example, the target stimulation signal value may be a target range from a first threshold magnitude value to a second threshold magnitude value. If the voltage magnitude of the stimulation signal is less than the first threshold magnitude value, the electrical stimulation might not be as effective at treating pain perceived by patient **105** as compared with scenarios in which the voltage magnitude of the stimulation signal is within the target range. On the other hand, if the voltage magnitude of the stimulation signal is greater than the second threshold magnitude value, the electrical stimulation might be inducing an uncomfortable (e.g., unwanted or painful) sensation perceived by patient **105** as compared with examples in which the voltage magnitude of the stimulation signal is within the target range. In some examples, IMD **110** may control the voltage magnitude of the stimulation signal to be within a target range by changing and/or setting one or more parameters of subsequent stimulation pulses (e.g., control pulses and/or informed pulses) delivered to patient **105** in response to measuring the voltage magnitude of one or more detected stimulation signals.

A target stimulation signal value (e.g., a target range or a target value) for characteristic values of the stimulation signals may, in some cases, be different depending on one or more conditions. In some examples, the target range may include an upper-bound value, a lower-bound value, a target characteristic value between the lower-bound value and the upper-bound value, or a target characteristic value plus and/or minus a tolerance value. In some examples, the upper-bound and the lower-bound of a target range of a characteristic of a stimulation signal may depend on an amplitude of the stimulation pulse which causes IMD **110** to sense the stimulation signal. For example, a first stimulation pulse including a first parameter value may cause IMD **110** to sense a first stimulation signal and a second stimulation pulse including a second parameter value may cause IMD **110** to sense a second stimulation signal, where the second parameter value is greater than the second parameter value. In at least some such cases, IMD **110** may compare a characteristic of the first stimulation signal to a first target range of characteristic values and IMD **110** may compare a characteristic of the second stimulation signal to a second target range of characteristic values, where the upper-bound value of the second target range is greater than the upper-bound value of the first target range and where the lower-bound value of the second target range is greater than the lower-bound value of the first target range. In this way, the target range of characteristic values corresponding to a characteristic of a stimulation signal may generally increase as the parameter of the stimulation pulse (e.g., an amplitude of the pulse or an area under the pulse) which causes IMD **110** to sense the stimulation signal increases.

Additionally, or alternatively, the target stimulation signal value (e.g., the target range) of characteristic values of the stimulation signals may depend on a posture of patient **105**. For example, IMD **110** may include an accelerometer (not illustrated in FIG. **1**) which is configured to generate an accelerometer signal. IMD **110** may be configured to determine, based on the accelerometer signal, a posture of patient **105**. The determined posture may be a posture of a set of postures including a standing posture, a seated posture, a supine posture, a prone posture, and a side-lying posture, as examples. IMD **110** may be configured to select the target range of characteristic values of a stimulation signal based on the determined posture of patient **105**. As discussed above, in some examples, the IMD **110** may be configured to select the target stimulation signal value of the stimulation signal based on a magnitude of the stimulation pulse which causes IMD **110** to sense the stimulation signal in addition to selecting the target range of characteristic values based on the posture of patient **105**. In fact, the target range of characteristic values for a particular stimulation signal may be defined by one or more "transfer functions," where each posture of the set of postures being associated with a respective transfer function.

As described herein, a transfer function may define a relationship between a magnitude of a stimulation pulse which causes IMD **110** to sense a stimulation signal and a target stimulation signal value of the stimulation signal. Each posture of patient **105** may be associated with a transfer function which defines the respective relationship between stimulation magnitude and the target stimulation signal value of the stimulation signal. In some examples, one or more transfer functions that are each associated with a respective posture may represent a linear function, meaning that such transfer functions define a linear relationship between the magnitude of a stimulation pulse and the target range of characteristic values of the stimulation signal

resulting from the stimulation pulse. However, this does not need to be the case. Transfer functions may represent any one or combination of functions including linear functions, quadratic functions, exponential functions, piecewise functions, power functions, polynomial functions, rational functions, logarithmic functions, and sinusoidal functions.

In some examples, a standing posture is associated with a first transfer function including a first slope, a sitting posture is associated with a second transfer function including a second slope, and a supine posture is associated with a third transfer function including a third slope. In some examples, the first transfer function, the second transfer function may each represent functions where a target range of characteristic values of one or more stimulation signals are plotted against a magnitude of a stimulation pulse which causes IMD **110** to sense the respective stimulation signal, where the target range of characteristic values are plotted on a y-axis of a graph, and the stimulation magnitude is plotted on an x-axis of the graph. In at least some such examples, the first slope of the first transfer function is greater than the second slope of the second transfer function, and the second slope of the second transfer function is greater than the third slope of the third transfer function. Consequently, at times when patient **105** is occupying a supine posture, the target stimulation signal value (e.g., a target range of characteristic values) is more sensitive to changes in stimulation amplitude as compared with times when patient **105** is standing or sitting.

Since the first transfer function, the second transfer function, and the third transfer function each have different slopes, IMD **110** may change the target stimulation signal value (e.g., the target range of characteristic values) based on detecting a change in the posture of patient **105**. For example, in response to IMD **110** determining that patient **105** is standing, IMD **110** may select a first target range including a first lower-bound value and a first upper-bound value. If stimulation magnitude is held constant and in response to IMD **110** determining that patient **105** is sitting, IMD **110** may select a second target range including a second lower-bound value and a second upper-bound value. Additionally, if stimulation magnitude is held constant and in response to IMD **110** determining that patient **105** is occupying a supine posture, IMD **110** may select a third target range including a third lower-bound value and a third upper-bound value. In some examples, the third upper-bound value may be greater than the second upper-bound value and the second upper-bound value may be greater than the first upper-bound value. Additionally, the third lower-bound value may be greater than the second lower-bound value and the second lower-bound value may be greater than the first lower-bound value.

In the example of FIG. **1**, IMD **110** is described as performing a plurality of processing and computing functions. However, external programmer **150** instead may perform one, several, or all of these functions. In this alternative example, IMD **110** functions to relay sensed signals to external programmer **150** for analysis, and external programmer **150** transmits instructions to IMD **110** to adjust the one or more parameters defining the electrical stimulation therapy based on analysis of the sensed signals. For example, IMD **110** may relay the sensed signal indicative of a stimulation signal to external programmer **150**. External programmer **150** may compare a characteristic value of the stimulation signal to the respective target range of characteristic values, and in response to the comparison, external programmer **150** may instruct IMD **110** to adjust one or more parameters that define the electrical stimulation pulses delivered to patient **105**.

In some examples, stimulation generation circuitry of IMD **110** may be configured to deliver at least one stimulation pulse between a time in which the stimulation generation circuitry delivers a first stimulation pulse and a time in which the stimulation generation circuitry delivers a second stimulation pulse which is based on a stimulation signal responsive to the first stimulation pulse. In some examples, stimulation generation circuitry of IMD **110** may be configured to deliver the second stimulation pulse consecutive to the first stimulation pulse.

In the example techniques described in this disclosure, the control stimulation parameters and the target stimulation signal value (e.g., a target range of characteristic values) of the stimulation signals may be initially set at the clinic but may be set and/or adjusted at home by patient **105**. Once a target stimulation signal value (e.g., a target range of characteristic values) are set, the example techniques allow for automatic adjustment of parameters of the stimulation pulses in order to maintain consistent volume of neural activation and consistent perception of therapy for patient **105** when the electrode-to-neuron distance changes. The ability to change the stimulation parameter values may also allow the therapy to have long term efficacy, with the ability to keep the intensity of the stimulation (e.g., as indicated by the detected stimulation signals) consistent by comparing the measured characteristic values of the stimulation signals to the target range of characteristic values. IMD **110** may perform these changes without intervention by a physician or patient **105**.

FIG. **2** is a block diagram illustrating an example configuration of components of IMD **200**, in accordance with one or more techniques of this disclosure. IMD **200** may be an example of IMD **110** of FIG. **1**. In the example shown in FIG. **2**, IMD **200** includes stimulation generation circuitry **202**, switch circuitry **204**, sensing circuitry **206**, communication circuitry **208**, processing circuitry **210**, storage device **212**, sensor(s) **222**, and power source **224**. As seen in FIG. **2**, sensor(s) **222** include acceleration sensor **223**.

In the example shown in FIG. **2**, storage device **212** stores therapy stimulation programs **214** and test stimulation programs **216** in separate memories within storage device **212** or separate areas within storage device **212**. Each stored therapy stimulation program of therapy stimulation programs **214** defines values for a set of electrical stimulation parameters (e.g., a stimulation parameter set), such as a stimulation electrode combination, electrode polarity, current or voltage amplitude, pulse width, pulse rate, and pulse shape. Each stored test stimulation programs **216** defines values for a set of electrical stimulation parameters (e.g., a control stimulation parameter set), such as a stimulation electrode combination, electrode polarity, current or voltage amplitude, pulse width, pulse rate, and pulse shape. Test stimulation programs **216** may also have additional information such as instructions regarding when to deliver control pulses based on the pulse width and/or frequency of the informed pulses defined in therapy stimulation programs **214**. In examples in which control pulses are provided to the patient without the need for informed pulses, a separate test stimulation program may not be needed. Instead, the test stimulation program for therapy that only includes control pulses may define the same control pulses as the corresponding therapy stimulation program for those control pulses.

Accordingly, in some examples, stimulation generation circuitry **202** generates electrical stimulation signals in

accordance with the electrical stimulation parameters noted above. Other ranges of stimulation parameter values may also be useful and may depend on the target stimulation site within patient **105**. While stimulation pulses are described, stimulation signals may be of any form, such as continuous-time signals (e.g., sine waves) or the like. Switch circuitry **204** may include one or more switch arrays, one or more multiplexers, one or more switches (e.g., a switch matrix or other collection of switches), or other electrical circuitry configured to direct stimulation signals from stimulation generation circuitry **202** to one or more of electrodes **232**, **234**, or directed sensed signals from one or more of electrodes **232**, **234** to sensing circuitry **206**. In other examples, stimulation generation circuitry **202** and/or sensing circuitry **206** may include sensing circuitry to direct signals to and/or from one or more of electrodes **232**, **234**, which may or may not also include switch circuitry **204**.

Sensing circuitry **206** monitors signals from any combination of electrodes **232**, **234**. In some examples, sensing circuitry **206** includes one or more amplifiers, filters, and analog-to-digital converters. Sensing circuitry **206** may be used to sense physiological signals, such as ECAPs. Additionally, or alternatively, sensing circuitry **206** may sense one or more stimulation pulses delivered to patient **105** via electrodes **232**, **234**. In some examples, sensing circuitry **206** detects electrical signals, such as stimulation signals and/or ECAPs from a particular combination of electrodes **232**, **234**. In some cases, the particular combination of electrodes for sensing ECAPs includes different electrodes than a set of electrodes **232**, **234** used to deliver stimulation pulses. Alternatively, in other cases, the particular combination of electrodes used for sensing ECAPs includes at least one of the same electrodes as a set of electrodes used to deliver stimulation pulses to patient **105**. Sensing circuitry **206** may provide signals to an analog-to-digital converter, for conversion into a digital signal for processing, analysis, storage, or output by processing circuitry **210**.

Communication circuitry **208** supports wireless communication between IMD **200** and an external programmer (not shown in FIG. **2**) or another computing device under the control of processing circuitry **210**. Processing circuitry **210** of IMD **200** may receive, as updates to programs, values for various stimulation parameters such as amplitude and electrode combination, from the external programmer via communication circuitry **208**. Updates to the therapy stimulation programs **214** and test stimulation programs **216** may be stored within storage device **212**. Communication circuitry **208** in IMD **200**, as well as communication circuits in other devices and systems described herein, such as the external programmer, may accomplish communication by radiofrequency (RF) communication techniques. In addition, communication circuitry **208** may communicate with an external medical device programmer (not shown in FIG. **2**) via proximal inductive interaction of IMD **200** with the external programmer. The external programmer may be one example of external programmer **150** of FIG. **1**. Accordingly, communication circuitry **208** may send information to the external programmer on a continuous basis, at periodic intervals, or upon request from IMD **110** or the external programmer.

Processing circuitry **210** may include any one or more of a microprocessor, a controller, a digital signal processor (DSP), an application specific integrated circuit (ASIC), a field-programmable gate array (FPGA), discrete logic circuitry, or any other processing circuitry configured to provide the functions attributed to processing circuitry **210** herein may be embodied as firmware, hardware, software or any combination thereof. Processing circuitry **210** controls stimulation generation circuitry **202** to generate stimulation signals according to therapy stimulation programs **214** and test stimulation programs **216** stored in storage device **212** to apply stimulation parameter values specified by one or more of programs, such as amplitude, pulse width, pulse rate, and pulse shape of each of the stimulation signals.

In the example shown in FIG. **2**, the set of electrodes **232** includes electrodes **232**A, **232**B, **232**C, and **232**D, and the set of electrodes **234** includes electrodes **234**A, **234**B, **234**C, and **234**D. In other examples, a single lead may include all eight electrodes **232** and **234** along a single axial length of the lead. Processing circuitry **210** also controls stimulation generation circuitry **202** to generate and apply the stimulation signals to selected combinations of electrodes **232**, **234**. In some examples, stimulation generation circuitry **202** includes a switch circuit (instead of, or in addition to, switch circuitry **204**) that may couple stimulation signals to selected conductors within leads **230**, which, in turn, deliver the stimulation signals across selected electrodes **232**, **234**. Such a switch circuit may be a switch array, switch matrix, multiplexer, or any other type of switching circuit configured to selectively couple stimulation energy to selected electrodes **232**, **234** and to selectively sense bioelectrical neural signals of a spinal cord of the patient (not shown in FIG. **2**) with selected electrodes **232**, **234**.

In other examples, however, stimulation generation circuitry **202** does not include a switch circuit and switch circuitry **204** does not interface between stimulation generation circuitry **202** and electrodes **232**, **234**. In these examples, stimulation generation circuitry **202** includes a plurality of pairs of voltage sources, current sources, voltage sinks, or current sinks connected to each of electrodes **232**, **234** such that each pair of electrodes has a unique signal circuit. In other words, in these examples, each of electrodes **232**, **234** is independently controlled via its own signal circuit (e.g., via a combination of a regulated voltage source and sink or regulated current source and sink), as opposed to switching signals between electrodes **232**, **234**.

Electrodes **232**, **234** on respective leads **230** may be constructed of a variety of different designs. For example, one or both of leads **230** may include one or more electrodes at each longitudinal location along the length of the lead, such as one electrode at different perimeter locations around the perimeter of the lead at each of the locations A, B, C, and D. In one example, the electrodes may be electrically coupled to stimulation generation circuitry **202**, e.g., via switch circuitry **204** and/or switching circuitry of the stimulation generation circuitry **202**, via respective wires that are straight or coiled within the housing of the lead and run to a connector at the proximal end of the lead. In another example, each of the electrodes of the lead may be electrodes deposited on a thin film. The thin film may include an electrically conductive trace for each electrode that runs the length of the thin film to a proximal end connector. The thin film may then be wrapped (e.g., a helical wrap) around an internal member to form the lead **230**. These and other constructions may be used to create a lead with a complex electrode geometry.

Although sensing circuitry **206** is incorporated into a common housing with stimulation generation circuitry **202** and processing circuitry **210** in FIG. **2**, in other examples, sensing circuitry **206** may be in a separate housing from IMD **200** and may communicate with processing circuitry **210** via wired or wireless communication techniques.

In some examples, one or more of electrodes **232** and **234** are suitable for sensing one or more ECAPs. For instance, electrodes **232** and **234** may sense the voltage amplitude of

a portion of the ECAP signals, where the sensed voltage amplitude is a characteristic of the ECAP signal.

In some examples, one or more of electrodes **232** and **234** are suitable for sensing stimulation signals. For instance, electrodes **232** and **234** may sense the voltage amplitude of a portion of the stimulation signals, where the sensed voltage amplitude is a characteristic of the stimulation signals. In some examples, one or more of electrodes **232** and **234** may sense a stimulation signal in response to one or more of electrodes **232** and **234** delivering a stimulation pulse to target tissue of patient **105**. In some examples, the one or more of electrodes **232** and **234** which sense the stimulation signal are not the same as the one or more of electrodes **232** and **234** which deliver the stimulation pulse.

Storage device **212** may be configured to store information within IMD **200** during operation. Storage device **212** may include a computer-readable storage medium or computer-readable storage device. In some examples, storage device **212** includes one or more of a short-term memory or a long-term memory. Storage device **212** may include, for example, random access memories (RAM), dynamic random access memories (DRAM), static random access memories (SRAM), magnetic discs, optical discs, flash memories, or forms of electrically programmable memories (EPROM) or electrically erasable and programmable memories (EEPROM). In some examples, storage device **212** is used to store data indicative of instructions for execution by processing circuitry **210**. As discussed above, storage device **212** is configured to store therapy stimulation programs **214**, test stimulation programs **216**, and target values **218**.

In some examples, stimulation generation circuitry **202** may be configured to deliver electrical stimulation therapy to patient **105**. In some examples, the electrical stimulation therapy may include a plurality of informed pulses. Additionally, stimulation generation circuitry **202** may be configured to deliver a plurality of control pulses, where the plurality of control pulses is interleaved with at least some informed pulses of the plurality of informed pulses. Stimulation generation circuitry may deliver the plurality of informed pulses and the plurality of control pulses to target tissue (e.g., spinal cord **120**) of patient **105** via electrodes **232**, **234** of leads **230**. By delivering such informed pulses and control pulses, stimulation generation circuitry **202** may cause IMD **200** to sense stimulation signals that are indicative of the delivered pulses Additionally, or alternatively, stimulation generation circuitry **202** may deliver control pulses that evoke detectable responsive ECAPs in the target tissue, the responsive ECAPs propagating through the target tissue before arriving back at electrodes **232**, **234**. Stimulation signals or ECAPs caused by or elicited by informed pulses may not be detectable by IMD **200**. In some examples, a different combination of electrodes **232**, **234** may sense responsive ECAPs and/or responsive stimulation signals than a combination of electrodes **232**, **234** that delivers informed pulses and a combination of electrodes **232**, **234** that delivers control pulses. Sensing circuitry **206** may be configured to detect the responsive ECAPs and/or the responsive stimulation signals via electrodes **232**, **234** and leads **230**. In other examples, stimulation generation circuitry **202** may be configured to deliver a plurality of control pulses, without any informed pulses, when control pulses also provide or contribute to a therapeutic effect for the patient.

Processing circuitry **210** may, in some cases, direct sensing circuitry **206** to continuously monitor for ECAPs and stimulation signals. In other cases, processing circuitry **210** may direct sensing circuitry **206** to monitor for ECAPs and stimulation signals based on signals from sensor(s) **222**. For example, processing circuitry **210** may activate sensing circuitry **206** based on an activity level of patient **105** exceeding an activity level threshold (e.g., acceleration sensor **223** rises above a threshold). Activating and deactivating sensing circuitry **206** may, in some examples, extend a battery life of power source **224**.

Processing circuitry **210** may determine whether electrical stimulation therapy delivered to target tissue of patient **105** via electrodes **232**, **234** elicits enough detectible ECAPs for processing circuitry **210** to determine therapy based on one or more characteristics of the respective detectible ECAPs. It may be beneficial for processing circuitry **210** to determine therapy based on characteristics of detectible ECAPs rather than characteristics of detectible stimulation signals, if possible. However, if not enough responsive ECAPs are detectible by sensing circuitry **206**, it may be beneficial for processing circuitry **210** to determine therapy based on one or more characteristics of respective stimulation signals, which are often still detectible even when some or all of elicited ECAPs are not detectible in response to a stimulation pulse. In addition, sensing circuitry **206** may still detect stimulation signals when the delivered stimulation pulses were insufficient to elicit a detectable ECAP signal (e.g., when the stimulation pulses are configured to be sub-threshold pulses).

In one example, to determine if the electrical stimulation therapy elicits enough detectible ECAPs, processing circuitry **210** is configured to perform a test to determine whether the plurality of pulses of the electrical stimulation therapy elicit greater than a threshold ratio of detectible ECAPs. For example, to perform the test, processing circuitry **210** may identify a set of ECAPs elicited by a sequence of consecutive pulses of the plurality of pulses. Subsequently, processing circuitry **210** may calculate a ratio of the set of ECAPs to the sequence of consecutive pulses. For example, processing circuitry **210** may first determine a number of ECAPs of the set of ECAPs and a number of pulses of the sequence of consecutive pulses, and then calculate a ratio of the number of ECAPs to the number of pulses.

There may be cases in which a particular one or more stimulation pulses of the sequence of consecutive pulses might not elicit ECAPs that are detectible by sensing circuitry **206**, but another one or more stimulation pulses of the sequence of consecutive pulses do elicit ECAPs that are detectible by sensing circuitry **206**. In such cases, processing circuitry **210** may be configured to determine therapy based on one or more characteristics of the detectible ECAPs rather than determine therapy based on one or more characteristics of detectible stimulation signals. In some examples, processing circuitry **210** may determine whether the ratio of detectible ECAPs to stimulation pulses is greater than the threshold ratio. In one or more cases where the ratio is greater than the threshold ratio, processing circuitry **210** may determine therapy based on characteristics of the detectible ECAPs. In one or more cases where the ratio is not greater than the threshold ratio, processing circuitry **210** may determine therapy based on characteristics of the detectible stimulation signals.

In some examples, responsive to determining that a plurality of pulses elicit greater than a threshold ratio of detectible ECAPs, processing circuitry **210** is configured to set, based on one or more characteristics of an ECAP, one or more parameters which at least partially define the one or more pulses deliverable by stimulation generation circuitry **202** after a stimulation pulse which elicits the respective

ECAP. In some examples, responsive to determining that a plurality of pulses do not elicit greater than a threshold ratio of detectible ECAPs, processing circuitry **210** is configured to set, based on one or more characteristics of a stimulation signal, one or more parameters which at least partially define the one or more pulses deliverable by stimulation generation circuitry **202** after a stimulation pulse which elicits the respective stimulation signal. In some examples, processing circuitry **210** may set one or more parameters which at least partially define the one or more pulses deliverable by stimulation generation circuitry **202** based on a combination of characteristics of one or more detectable ECAPs and characteristics of one or more detectible stimulation signals.

Stimulation generation circuitry **202** may be configured to deliver one or more stimulation pulses, at least one of which may cause sensing circuitry **206** to sense a stimulation signal in response to the delivery of the respective pulse. In some examples, to sense a stimulation signal, sensing circuitry **206** may detect, via any one or combination of electrodes **232**, **234**, one or more electrical signals which are generated by stimulation generation circuitry **202** and delivered to patient **105** via any one or combination of electrodes **232**, **234**. In some examples, stimulation signals may include information which is useful for determining one or more parameters of upcoming therapy pulses generated by stimulation generation circuitry **202**. For example, information included by a stimulation signal may include one or more characteristics which indicate an efficacy of therapy delivered to patient **105** via electrodes **232**, **234**. In some cases, the one or more characteristics may reflect a separation between one or more of electrodes **232**, **234** and target tissue of patient **105** (e.g., spinal cord **120**). Such a distance between electrodes **232**, **234** and spinal cord **120** may be relevant to determining therapy since a smaller intensity (e.g., amplitude and/or pulse length) of therapy pulses is required to stimulate a nerve if electrodes **232**, **234** move closer to spinal cord **120** and vice versa.

Processing circuitry **210** may be configured to compare a characteristic value of a stimulation signal to a target stimulation signal value and adjust a stimulation parameter value based on the comparison. For example, processing circuitry may be configured to determine whether a characteristic value of a stimulation signal is within a range from a first threshold characteristic value to a second threshold characteristic value. In some examples, the characteristic value may include an amplitude of the stimulation signal, an amplitude of a portion of the stimulation signal, a slope of a portion of the stimulation signal, an area under a curve of at least a portion of the stimulation signal, or any combination thereof. In this way, sensing circuitry **206** may be configured to determine whether an amplitude of a portion of the stimulation signal is within a range from a first threshold amplitude value for the portion of the stimulation signal to a second threshold amplitude value for the portion of the stimulation signal, for example, but this is not required. The characteristic value may represent any measurable characteristic of a stimulation signal.

Responsive to determining that the characteristic value of the stimulation signal is not within a range from a first threshold characteristic value to a second threshold characteristic value, processing circuitry **210** may change one or more parameters which at least partially define one or more pulses deliverable by the stimulation generation circuitry after the stimulation signal as compared with the one or more parameters which at least partially define one or more pulses deliverable by the stimulation generation circuitry before the stimulation signal. In some examples, processing circuitry **210** may determine that the characteristic value is lower than the first threshold characteristic value.

In response to the characteristic value being lower than the first threshold characteristic value, processing circuitry **210** may be configured to increase (e.g., increment) one or more parameters which at least partially define one or more pulses deliverable by stimulation generation circuitry **202** after the stimulation signal (e.g., increase one or more parameters which define pulses of therapy stimulation programs **214** and/or test stimulation programs **216**). In some examples, processing circuitry **210** may increase the one or more parameters proportional to an amount that the characteristic value is lower than the first threshold characteristic value. In some examples, processing circuitry **210** may increase the one or more parameters by a predetermined amount no matter the amount that the characteristic value is lower than the first threshold characteristic value. In some examples, processing circuitry **210** may increase the one or more parameters according to a function, where an input to the function is the characteristic value of the stimulation signal.

In response to the characteristic value being greater than the second threshold characteristic value, processing circuitry **210** may be configured to decrease (e.g., decrement) one or more parameters which at least partially define one or more pulses deliverable by stimulation generation circuitry **202** after the stimulation signal (e.g., decrease one or more parameters which define pulses of therapy stimulation programs **214** and/or test stimulation programs **216**). In some examples, processing circuitry **210** may decrease the one or more parameters proportional to an amount that the characteristic value is greater than the second threshold characteristic value. In some examples, processing circuitry **210** may decrease the one or more parameters by a predetermined amount no matter the amount that the characteristic value is greater than the second threshold characteristic value. In some examples, processing circuitry **210** may decrease the one or more parameters according to a function, where an input to the function is the characteristic value of the stimulation signal.

Processing circuitry **210** may maintain one or more parameters of which at least partially define one or more pulses deliverable by stimulation generation circuitry **202** after a respective stimulation signal responsive to determining that a value of a characteristic of the stimulation signal is within a range from a first threshold characteristic value to a second threshold characteristic value. For example, if the characteristic of the stimulation signal is within the range, this may indicate that the one or more parameters which at least partially define one or more pulses deliverable by stimulation generation circuitry **202** are within a desired range.

A characteristic value of a stimulation signal may, in some cases, depend on one or more parameters of the delivered pulse (e.g., pulse amplitude, pulse duration, area under a curve of the pulse, pulse shape, pulse slope, or any combination thereof) from which sensing circuitry **206** detects one or more stimulation signal. For example, determining therapy based on a stimulation signal may, in some cases, depend on an amplitude of the pulse which causes sensing circuitry **206** to detect the stimulation signal. This is because sensing circuitry **206** senses stimulation signals by detecting electrical signals indicative of stimulation pulses delivered by electrodes **232**, **234**. In this way, it may be expected that a first stimulation pulse having a first amplitude will cause sensing circuitry **206** to detect a stimulation signal having an amplitude within a first range of amplitude values. Addi-

tionally, it may be expected that a second stimulation pulse having a second amplitude will cause sensing circuitry **206** to detect a stimulation signal having an amplitude within a second range of amplitude values. If the first amplitude of the first stimulation pulse is lower than the second amplitude of the second stimulation pulse, a lower-bound of the first range may be lower than a lower-bound of the second range and an upper-bound of the first range may be lower than an upper-bound of the second range. In some examples, a range of target amplitude values for a stimulation signal may be linearly related to an amplitude of a stimulation pulse which causes sensing circuitry **206** to detect the stimulation signal. Storage device **212** may store target values **218** which include a set of target ranges and other target values, where each target range and target value of target values **218** corresponds to a respective stimulation pulse amplitude value of a set of stimulation pulse amplitude values.

Determining therapy based on one or more stimulation signals may, in some cases, depend on a posture of patient **105**. For example, processing circuitry **210** may be configured to determine a posture of patient **105** based on an acceleration signal generated by acceleration sensor **223**. In some examples, the accelerometer signal includes a vertical component, a lateral component, and a frontal component corresponding to a vertical axis, a lateral axis, and a frontal axis, respectively. In this way, the accelerometer signal represents a three-dimensional measurement of acceleration. It may be beneficial for processing circuitry **210** to analyze one or more of the vertical axis, the lateral axis, and the frontal axis in order to determine a posture of patient **105**.

In some examples, acceleration sensor **223** is configured to generate an accelerometer signal. Processing circuitry **210** is configured to identify, based on the accelerometer signal, a posture of a set of postures which patient **105** is occupying. The set of postures may include, for example, a standing posture, a sitting posture, a supine posture, a prone posture, a side-lying posture, or any combination thereof. In some examples, expected parameter values of the accelerometer signal corresponding to each posture of the set of postures are stored in storage device **212**. Subsequently, processing circuitry **210** may select, based on the identified posture, a target stimulation signal value (e.g., a target range of characteristic values) for a stimulation signal sensed by IMD **200** in response to a delivery of a corresponding stimulation pulses. For example, if stimulation generation circuitry **202** generates a stimulation pulse having a stimulation amplitude and delivers the stimulation pulse to target tissue of patient **105** via one or a combination of electrodes **232**, **234**, processing circuitry **210** may select, based on a posture of patient **105** during the delivery of the stimulation pulse, a target range for a characteristic of the resulting stimulation signal sensed by sensing circuitry **106**. Subsequently, processing circuitry **210** may determine whether to change one or more parameters of therapy stimulation programs **314** and/or test stimulation programs **216** based on whether the characteristic value is within the target range of characteristic values selected based on the posture of patient **105**.

In some examples, processing circuitry **210** is configured to identify, based on the accelerometer signal, a posture of a set of postures which patient **105** is occupying while a stimulation pulse is delivered and identify an amplitude of the stimulation pulse. Subsequently, processing circuitry **210** may select a target range of characteristic values for a characteristic of a stimulation signal sensed by sensing circuitry **206** in response to the delivery of the stimulation pulse based on both of the posture of patient **105** and the amplitude of the stimulation pulse. For example, target values **218** may include a respective transfer function corresponding to each posture of the set of postures. Each transfer function represents a relationship (e.g., a linear relationship) between the amplitude of a stimulation pulse and the target stimulation signal value (e.g., a target range of characteristic values) for a stimulation signal sensed by IMD **200** in response to the delivery of the stimulation pulse. As such, processing circuitry **210** may, when evaluating whether to change one or more parameters of upcoming stimulation pulses, first select a transfer function corresponding to a present stimulation pulse and subsequently select a target range of characteristics based on the amplitude of the present stimulation pulse, but this is not required. Processing circuitry **210** may first analyze the amplitude of the stimulation pulse and subsequently determine the posture of patient **105**, in some cases.

In some examples, processing circuitry **210** is configured to determine, based on the accelerometer signal generated by acceleration sensor **223**, a transition from a first posture to a second posture of the set of postures. Responsive to determining the transition from the first posture to the second posture, processing circuitry **210** is configured to update the target stimulation signal value (e.g., the target range of characteristic values) for a respective sensed stimulation signal from a first target stimulation signal value to a second target stimulation signal value. In some examples, the detected change in posture may trigger the transition from a first target range to a second target range, but this is not required. In some cases, processing circuitry **102** may monitor the posture of patient **105** and the amplitude of stimulation pulses generated by stimulation generation circuitry **202** in real time or near real-time. Accordingly, processing circuitry **210** may set the range of target characteristic values for responsive stimulation signals in real time or near real-time.

Power source **224** is configured to deliver operating power to the components of IMD **200**. Power source **224** may include a battery and a power generation circuit to produce the operating power. In some examples, the battery is rechargeable to allow extended operation. In some examples, recharging is accomplished through proximal inductive interaction between an external charger and an inductive charging coil within IMD **200**. Power source **224** may include any one or more of a plurality of different battery types, such as nickel cadmium batteries and lithium ion batteries.

FIG. **3** is a block diagram illustrating an example configuration of components of external programmer **300**, in accordance with one or more techniques of this disclosure. External programmer **300** may be an example of external programmer **150** of FIG. **1**. Although external programmer **300** may generally be described as a hand-held device, external programmer **300** may be a larger portable device or a more stationary device. In addition, in other examples, external programmer **300** may be included as part of an external charging device or include the functionality of an external charging device. As illustrated in FIG. **3**, external programmer **300** may include processing circuitry **352**, storage device **354**, user interface **356**, telemetry circuitry **358**, and power source **360**. Storage device **354** may store instructions that, when executed by processing circuitry **352**, cause processing circuitry **352** and external programmer **300** to provide the functionality ascribed to external programmer **300** throughout this disclosure. Each of these components, circuitry, or modules, may include electrical circuitry that is configured to perform some, or all of the functionality described herein. For example, processing circuitry **352** may

include processing circuitry configured to perform the processes discussed with respect to processing circuitry **352**.

In general, external programmer **300** includes any suitable arrangement of hardware, alone or in combination with software and/or firmware, to perform the techniques attributed to external programmer **300**, and processing circuitry **352**, user interface **356**, and telemetry circuitry **358** of external programmer **300**. In various examples, external programmer **300** may include one or more processors, such as one or more microprocessors, DSPs, ASICs, FPGAs, or any other equivalent integrated or discrete logic circuitry, as well as any combinations of such components. External programmer **300** also, in various examples, may include a storage device **354**, such as RAM, ROM, PROM, EPROM, EEPROM, flash memory, a hard disk, a CD-ROM, including executable instructions for causing the one or more processors to perform the actions attributed to them. Moreover, although processing circuitry **352** and telemetry circuitry **358** are described as separate modules, in some examples, processing circuitry **352** and telemetry circuitry **358** are functionally integrated. In some examples, processing circuitry **352** and telemetry circuitry **358** correspond to individual hardware units, such as ASICs, DSPs, FPGAs, or other hardware units.

Storage device **354** (e.g., a storage device) may store instructions that, when executed by processing circuitry **352**, cause processing circuitry **352** and external programmer **300** to provide the functionality ascribed to external programmer **300** throughout this disclosure. For example, storage device **354** may include instructions that cause processing circuitry **352** to obtain a parameter set from memory, select a spatial electrode movement pattern, or receive a user input and send a corresponding command to IMD **200**, or instructions for any other functionality. In addition, storage device **354** may include a plurality of programs, where each program includes a parameter set that defines stimulation pulses, such as control pulses and/or informed pulses. Storage device **354** may also store data received from a medical device (e.g., IMD **110**). For example, storage device **354** may store stimulation signal and/or ECAP related data recorded at a sensing module of the medical device, and storage device **354** may also store data from one or more sensors of the medical device.

User interface **356** may include a button or keypad, lights, a speaker for voice commands, a display, such as a liquid crystal (LCD), light-emitting diode (LED), or organic light-emitting diode (OLED). In some examples the display includes a touch screen. User interface **356** may be configured to display any information related to the delivery of electrical stimulation, identified patient behaviors, sensed patient parameter values, patient behavior criteria, or any other such information. User interface **356** may also receive user input via user interface **356**. The input may be, for example, in the form of pressing a button on a keypad or selecting an icon from a touch screen. The input may request starting or stopping electrical stimulation, the input may request a new spatial electrode movement pattern or a change to an existing spatial electrode movement pattern, of the input may request some other change to the delivery of electrical stimulation.

Telemetry circuitry **358** may support wireless communication between the medical device and external programmer **300** under the control of processing circuitry **352**. Telemetry circuitry **358** may also be configured to communicate with another computing device via wireless communication techniques, or direct communication through a wired connection. In some examples, telemetry circuitry **358** provides wireless communication via an RF or proximal inductive medium. In some examples, telemetry circuitry **358** includes an antenna, which may take on a variety of forms, such as an internal or external antenna.

Examples of local wireless communication techniques that may be employed to facilitate communication between external programmer **300** and IMD **110** include RF communication according to the 802.11 or Bluetooth® specification sets or other standard or proprietary telemetry protocols. In this manner, other external devices may be capable of communicating with external programmer **300** without needing to establish a secure wireless connection. As described herein, telemetry circuitry **358** may be configured to transmit a spatial electrode movement pattern or other stimulation parameter values to IMD **110** for delivery of electrical stimulation therapy.

In some examples, selection of stimulation parameters or therapy stimulation programs are transmitted to the medical device for delivery to a patient (e.g., patient **105** of FIG. **1**). In other examples, the therapy may include medication, activities, or other instructions that patient **105** must perform themselves or a caregiver perform for patient **105**. In some examples, external programmer **300** provides visual, audible, and/or tactile notifications that indicate there are new instructions. External programmer **300** requires receiving user input acknowledging that the instructions have been completed in some examples.

According to the techniques of the disclosure, user interface **356** of external programmer **300** receives an indication from a clinician instructing a processor of the medical device to update one or more therapy stimulation programs or to update one or more test stimulation programs. Updating therapy stimulation programs and test stimulation programs may include changing one or more parameters of the stimulation pulses delivered by the medical device according to the programs, such as amplitude, pulse width, frequency, and pulse shape of the informed pulses and/or control pulses. User interface **356** may also receive instructions from the clinician commanding any electrical stimulation, including control pulses and/or informed pulses to commence or to cease.

Power source **360** is configured to deliver operating power to the components of external programmer **300**. Power source **360** may include a battery and a power generation circuit to produce the operating power. In some examples, the battery is rechargeable to allow extended operation. Recharging may be accomplished by electrically coupling power source **360** to a cradle or plug that is connected to an alternating current (AC) outlet. In addition, recharging may be accomplished through proximal inductive interaction between an external charger and an inductive charging coil within external programmer **300**. In other examples, traditional batteries (e.g., nickel cadmium or lithium ion batteries) may be used. In addition, external programmer **300** may be directly coupled to an alternating current outlet to operate.

FIG. **4** is a graph **402** of example evoked compound action potentials (ECAPs) sensed for respective stimulation pulses, in accordance with one or more techniques of this disclosure. As shown in FIG. **4**, graph **402** shows example ECAP signal **404** (dotted line) and ECAP signal **406** (solid line). In some examples, each of ECAP signals **404** and **406** are sensed from stimulation pulses (e.g., a control pulse) that were delivered from a guarded cathode, where the stimulation pulses are bi-phasic pulses including an interphase interval between each positive and negative phase of the pulse. In some such examples, the guarded cathode includes

stimulation electrodes located at the end of an 8-electrode lead (e.g., leads **130** of FIG. **1**) while two sensing electrodes are provided at the other end of the 8-electrode lead. ECAP signal **404** illustrates the voltage amplitude sensed as a result from a sub-detection threshold stimulation pulse, or a stimulation pulse which results in no detectable ECAP. It is noted that monophasic, tri-phasic, or pulses with another quantity of phases may be in other examples.

Peaks **408** of ECAP signal **404** are detected and represent stimulation signals of the delivered stimulation pulse. However, no propagating signal is detected after the stimulation signal in ECAP signal **404** because the stimulation pulse had an intensity (e.g., an amplitude and/or pulse width) that was "sub-threshold" or below a detection threshold (e.g., a sub-detection threshold) and/or below a propagation threshold (e.g., a sub-propagation threshold).

In contrast to ECAP signal **404**, ECAP signal **406** represents the voltage amplitude detected from a supra-detection stimulation threshold stimulation pulse. Peaks **408** of ECAP signal **406** are detected and represent stimulation signals of the delivered stimulation pulse. After peaks **408**, ECAP signal **406** also includes peaks P**1**, N**1**, and P**2**, which are three typical peaks representative of propagating action potentials from an ECAP. The example duration of the stimulation signal and peaks P**1**, N**1**, and P**2** is approximately 1 millisecond (ms).

When detecting the ECAP of ECAP signal **406**, different characteristics may be identified. For example, the characteristic of the ECAP may be the amplitude between N**1** and P**2**. This N**1**-P**2** amplitude may be easily detectable even if the stimulation signal impinges on P**1**, a relatively large signal, and the N**1**-P**2** amplitude may be minimally affected by electronic drift in the signal. In other examples, the characteristic of the ECAP used to control subsequent stimulation pulses (e.g., control pulses and/or informed pulses) may be an amplitude of P**1**, N**1**, or P**2** with respect to neutral or zero voltage. In some examples, the characteristic of the ECAP used to control subsequent stimulation pulses is a sum of two or more of peaks P**1**, N**1**, or P**2**. In other examples, the characteristic of ECAP signal **406** may be the area under one or more of peaks P**1**, N**1**, and/or P**2**. In other examples, the characteristic of the ECAP may be a ratio of one of peaks P**1**, N**1**, or P**2** to another one of the peaks. In some examples, the characteristic of the ECAP is a slope between two points in the ECAP signal, such as the slope between N**1** and P**2**. In other examples, the characteristic of the ECAP may be the time between two points of the ECAP, such as the time between N**1** and P**2**.

The time between when the stimulation pulse is delivered and a point in the ECAP signal may be referred to as a latency of the ECAP and may indicate the types of fibers being captured by the stimulation pulse (e.g., a control pulse). ECAP signals with lower latency (i.e., smaller latency values) indicate a higher percentage of nerve fibers that have faster propagation of signals, whereas ECAP signals with higher latency (i.e., larger latency values) indicate a higher percentage of nerve fibers that have slower propagation of signals. Latency may also refer to the time between an electrical feature is detected at one electrode and then detected again at a different electrode. This time, or latency, is inversely proportional to the conduction velocity of the nerve fibers. Other characteristics of the ECAP signal may be used in other examples.

The amplitude of the ECAP signal increases with increased amplitude of the stimulation pulse, as long as the pulse amplitude is greater than threshold such that nerves depolarize and propagate the signal. The target ECAP characteristic (e.g., the target ECAP amplitude) may be determined from the ECAP signal detected from a stimulation pulse (or a control pulse) when informed pulses are determined to deliver effective therapy to patient **105**. The ECAP signal thus is representative of the distance between the stimulation electrodes and the nerves appropriate for the stimulation parameter values of the informed pulses delivered at that time. Therefore, IMD **110** may attempt to use detected changes to the measured ECAP characteristic value to change therapy pulse parameter values and maintain the target ECAP characteristic value during therapy pulse delivery.

FIG. **5**A is a timing diagram **500**A illustrating an example of electrical stimulation pulses, respective stimulation signals, and respective sensed ECAPs, in accordance with one or more techniques of this disclosure. For convenience, FIG. **5**A is described with reference to IMD **200** of FIG. **2**. As illustrated, timing diagram **500**A includes first channel **502**, a plurality of stimulation pulses **504**A-**504**N (collectively "stimulation pulses **504**"), second channel **506**, a plurality of respective ECAPs **508**A-**508**N (collectively "ECAPs **508**"), and a plurality of stimulation signals **509**A-**509**N (collectively "stimulation signals **509**"). In some examples, stimulation pulses **504** may represent control pulses which are configured to elicit ECAPs **508** that are detectible by IMD **200**, but this is not required. Stimulation pulses **504** may represent any type of pulse that is deliverable by IMD **200**. In the example of FIG. **5**A, IMD **200** can deliver therapy with control pulses instead of, or without, informed pulses.

First channel **502** is a time/voltage (and/or current) graph indicating the voltage (or current) of at least one electrode of electrodes **232**, **234**. In one example, the stimulation electrodes of first channel **502** may be located on the opposite side of the lead as the sensing electrodes of second channel **506**. Stimulation pulses **504** may be electrical pulses delivered to the spinal cord of the patient by at least one of electrodes **232**, **234**, and stimulation pulses **504** may be balanced biphasic square pulses with an interphase interval. In other words, each of stimulation pulses **504** are shown with a negative phase and a positive phase separated by an interphase interval. For example, a stimulation pulse **504** may have a negative voltage for the same amount of time and amplitude that it has a positive voltage. It is noted that the negative voltage phase may be before or after the positive voltage phase. Stimulation pulses **504** may be delivered according to test stimulation programs **216** stored in storage device **212** of IMD **200**, and test stimulation programs **216** may be updated according to user input via an external programmer and/or may be updated according to a signal from sensor(s) **222**. In one example, stimulation pulses **504** may have a pulse width of less than approximately 300 microseconds (e.g., the total time of the positive phase, the negative phase, and the interphase interval is less than 300 microseconds). In another example, stimulation pulses **504** may have a pulse width of approximately 100 us for each phase of the bi-phasic pulse. As illustrated in FIG. **5**A, stimulation pulses **504** may be delivered via channel **502**. Delivery of stimulation pulses **504** may be delivered by leads **230** in a guarded cathode electrode combination. For example, if leads **230** are linear 8-electrode leads, a guarded cathode combination is a central cathodic electrode with anodic electrodes immediately adjacent to the cathodic electrode.

Second channel **506** is a time/voltage (and/or current) graph indicating the voltage (or current) of at least one electrode of electrodes **232**, **234**. In one example, the electrodes of second channel **506** may be located on the opposite

side of the lead as the electrodes of first channel **502**. ECAPs **508** may be sensed at electrodes **232**, **234** from the spinal cord of the patient in response to stimulation pulses **504**. ECAPs **508** are electrical signals which may propagate along a nerve away from the origination of stimulation pulses **504**. In one example, ECAPs **508** are sensed by different electrodes than the electrodes used to deliver stimulation pulses **504**. As illustrated in FIG. **5**A, ECAPs **508** may be recorded on second channel **506**.

Stimulation signals **509**A, **509**B, and **509**N may be sensed by leads **230** and sensing circuitry **206** and may be sensed during the same period of time as the delivery of stimulation pulses **504**. Since the stimulation signals may have a greater amplitude and intensity than ECAPs **508**, any ECAPs arriving at IMD **200** during the occurrence of stimulation signals **509** might not be adequately sensed by sensing circuitry **206** of IMD **200**. However, ECAPs **508** may be sufficiently sensed by sensing circuitry **206** because each ECAP **508**, or at least a portion of ECAP **508** used as feedback for stimulation pulses **504**, falls after the completion of each a stimulation pulse **504**. As illustrated in FIG. **5**A, stimulation signals **509** and ECAPs **508** may be recorded on channel **506**. In some examples, ECAPs **508** may not follow respective stimulation signals **509** when ECAPs are not elicited by stimulation pulses **504** or the amplitude of ECAPs is too low to be detected (e.g., below the detection threshold).

FIG. **5**B is a timing diagram **500**B illustrating one example of electrical stimulation pulses, respective stimulation signals, and respective sensed ECAPs, in accordance with one or more techniques of this disclosure. For convenience, FIG. **5**B is described with reference to IMD **200** of FIG. **2**. As illustrated, timing diagram **500**B includes first channel **510**, a plurality of control pulses **512**A-**512**N (collectively "control pulses **512**"), second channel **520**, a plurality of informed pulses **524**A-**524**N (collectively "informed pulses **524**") including passive recharge phases **526**A-**526**N (collectively "passive recharge phases **526**"), third channel **530**, a plurality of respective ECAPs **536**A-**536**N (collectively "ECAPs **536**"), and a plurality of stimulation signals **538**A-**538**N (collectively "stimulation signals **538**").

First channel **510** is a time/voltage (and/or current) graph indicating the voltage (or current) of at least one electrode of electrodes **232**, **234**. In one example, the stimulation electrodes of first channel **510** may be located on the opposite side of the lead as the sensing electrodes of third channel **530**. Control pulses **512** may be electrical pulses delivered to the spinal cord of the patient by at least one of electrodes **232**, **234**, and control pulses **512** may be balanced biphasic square pulses with an interphase interval. In other words, each of control pulses **512** are shown with a negative phase and a positive phase separated by an interphase interval. For example, a control pulse **512** may have a negative voltage for the same amount of time that it has a positive voltage. It is noted that the negative voltage phase may be before or after the positive voltage phase. Control pulses **512** may be delivered according to test stimulation programs **216** stored in storage device **212** of IMD **200**, and test stimulation programs **216** may be updated according to user input via an external programmer and/or may be updated according to a signal from sensor(s) **222**. In one example, control pulses **512** may have a pulse width of less than approximately 300 microseconds (e.g., the total time of the positive phase, the negative phase, and the interphase interval is less than 300 microseconds). In another example, control pulses **512** may have a pulse width of approximately 100 us for each phase of the bi-phasic pulse. As illustrated in FIG. **5**B, control pulses **512** may be delivered via first channel **510**. Delivery of control pulses **512** may be delivered by leads **230** in a guarded cathode electrode combination. For example, if leads **230** are linear 8-electrode leads, a guarded cathode combination is a central cathodic electrode with anodic electrodes immediately adjacent to the cathodic electrode.

Second channel **520** is a time/voltage (and/or current) graph indicating the voltage (or current) of at least one electrode of electrodes **232**, **234** for the informed pulses. In one example, the electrodes of second channel **520** may partially or fully share common electrodes with the electrodes of first channel **510** and third channel **530**. Informed pulses **524** may also be delivered by the same leads **230** that are configured to deliver control pulses **512**. Informed pulses **524** may be interleaved with control pulses **512**, such that the two types of pulses are not delivered during overlapping periods of time. However, informed pulses **524** may or may not be delivered by exactly the same electrodes that deliver control pulses **512**. Informed pulses **524** may be monophasic pulses with pulse widths of greater than approximately 300 us and less than approximately 1000 μs. In fact, informed pulses **524** may be configured to have longer pulse widths than control pulses **512**. As illustrated in FIG. **5**B, informed pulses **524** may be delivered on second channel **520**.

Informed pulses **524** may be configured for passive recharge. For example, each informed pulse **524** may be followed by a passive recharge phase **526** to equalize charge on the stimulation electrodes. Unlike a pulse configured for active recharge, where remaining charge on the tissue following a stimulation pulse is instantly removed from the tissue by an opposite applied charge, passive recharge allows tissue to naturally discharge to some reference voltage (e.g., ground or a rail voltage) following the termination of the therapy pulse. In some examples, the electrodes of the medical device may be grounded at the medical device body. In this case, following the termination of informed pulse **524**, the charge on the tissue surrounding the electrodes may dissipate to the medical device, creating a rapid decay of the remaining charge at the tissue following the termination of the pulse. This rapid decay is illustrated in passive recharge phases **526**. Passive recharge phase **526** may have a duration in addition to the pulse width of the preceding informed pulse **524**. In other examples (not pictured in FIG. **5**B), informed pulses **524** may be bi-phasic pulses having a positive and negative phase (and, in some examples, an interphase interval between each phase) which may be referred to as pulses including active recharge. An informed pulse that is a bi-phasic pulse may or may not have a following passive recharge phase.

Third channel **530** is a time/voltage (and/or current) graph indicating the voltage (or current) of at least one electrode of electrodes **232**, **234**. In one example, the electrodes of third channel **530** may be located on the opposite side of the lead as the electrodes of first channel **510**. ECAPs **536** may be sensed at electrodes **232**, **234** from the spinal cord of the patient in response to control pulses **512**. ECAPs **536** are electrical signals which may propagate along a nerve away from the origination of control pulses **512**. In one example, ECAPs **536** are sensed by different electrodes than the electrodes used to deliver control pulses **512**. As illustrated in FIG. **5**B, ECAPs **536** may be recorded on third channel **530**.

Stimulation signals **538**A, **538**B, and **538**N may be sensed by leads **230** and may be sensed during the same period of time as the delivery of control pulses **512** and informed pulses **524**. Since the stimulation signals may have a greater amplitude and intensity than ECAPs **536**, any ECAPs arriv-

ing at IMD **200** during the occurrence of stimulation signals **538** may not be adequately sensed by sensing circuitry **206** of IMD **200**. However, ECAPS **536** may be sufficiently sensed by sensing circuitry **206** because each ECAP **536** falls after the completion of each a control pulse **512** and before the delivery of the next informed pulse **524**. As illustrated in FIG. **5**B, stimulation signals **538** and ECAPs **536** may be recorded on channel **530**.

FIG. **6**A is a timing diagram **600**A illustrating an example of electrical stimulation pulses, respective stimulation signals, and respective sensed ECAPs, in accordance with one or more techniques of this disclosure. For convenience, FIG. **6**A is described with reference to IMD **200** of FIG. **2**. As illustrated, timing diagram **600**A includes first channel **602**, a plurality of stimulation pulses **604**A-**604**N (collectively "stimulation pulses **604**"), second channel **606**, a plurality of respective ECAPs **608**A-**608**N (collectively "ECAPs **608**"), and a plurality of stimulation signals **609**A-**609**N (collectively "stimulation signals **609**"). In some examples, stimulation pulses **604** may represent control pulses which are configured to elicit ECAPs **608** that are detectible by IMD **200**, but this is not required. Stimulation pulses **604** may represent any type of pulse that is deliverable by IMD **200**. In the example of FIG. **6**A, IMD **200** can deliver therapy with control pulses instead of, or without, informed pulses.

Timing diagram **600**A of FIG. **6**A may be substantially the same as timing diagram **500**A FIG. **5**A except that stimulation pulse **604**A and stimulation pulse **604**N do not evoke an ECAP that is detectible by IMD **200**. Although stimulation pulse **604**B emits ECAP **608**B, which is detectible by IMD **200**, it may be the case that IMD **200** does not sense enough detectible ECAPs for therapy determination in the example of FIG. **6**A. As such, IMD **200** may determine one or more characteristics of stimulation signals **609** in order to determine one or more parameters of upcoming stimulation pulses following stimulation pulse **604**N. For example, IMD **200** may determine an amplitude of at least a portion of each stimulation signal of stimulation signals **609** and determine the one or more parameters of the upcoming stimulation pulses based on the determined amplitudes. Although stimulation signals **609** are illustrated as square pulses, stimulation signals **609** may include other shapes and/or waveforms, in some examples. In some examples, each stimulation signal of stimulation signals **509** may include two or more phases. Processing circuitry **210** of IMD **200** may analyze the two or more phases of stimulation signals **509** in order to determine therapy.

FIG. **6**B is a timing diagram **600**B illustrating one example of electrical stimulation pulses, respective stimulation signals, and respective sensed ECAPs, in accordance with one or more techniques of this disclosure. For convenience, FIG. **6**B is described with reference to IMD **200** of FIG. **2**. As illustrated, timing diagram **600**B includes first channel **610**, a plurality of control pulses **612**A-**612**N (collectively "control pulses **612**"), second channel **620**, a plurality of informed pulses **624**A-**624**N (collectively "informed pulses **624**") including passive recharge phases **626**A-**626**N (collectively "passive recharge phases **626**"), third channel **630**, a plurality of respective ECAPs **636**A-**636**N (collectively "ECAPs **636**"), and a plurality of stimulation signals **638**A-**638**N (collectively "stimulation signals **638**").

Timing diagram **600**B of FIG. **6**B may be substantially the same as timing diagram **500**B FIG. **5**B except that control pulse **612**A and control pulse **612**N do not evoke an ECAP that is detectible by IMD **200**. Although control pulse **612**B emits ECAP **636**B, which is detectible by IMD **200**, it may be the case that IMD **200** does not sense enough detectible ECAPs for therapy determination in the example of FIG. **6**B. As such, IMD **200** may determine one or more characteristics of stimulation signals **638** in order to determine one or more parameters of upcoming stimulation pulses following control pulse **612**N. For example, IMD **200** may determine an amplitude of at least a portion of each stimulation signal of stimulation signals **638** and determine the one or more parameters of the upcoming stimulation pulses based on the determined amplitudes. Although stimulation signals **638** are illustrated as square pulses, stimulation signals **639** may include other shapes and/or waveforms, in some examples. In some examples, each stimulation signal of stimulation signals **638** may include two or more phases. Processing circuitry **210** of IMD **200** may analyze the two or more phases of stimulation signals **638** in order to determine therapy.

FIG. **7** is a timing diagram **700** illustrating another example of electrical stimulation pulses, respective stimulation signals, and respective ECAPs, in accordance with one or more techniques of this disclosure. For convenience, FIG. **7** is described with reference to IMD **200** of FIG. **2**. As illustrated, timing diagram **700** includes first channel **710**, a plurality of control pulses **712**A-**712**N (collectively "control pulses **712**"), second channel **720**, a plurality of informed pulses **724**A-**724**B (collectively "informed pulses **724**") including passive recharge phases **726**A-**726**B (collectively "passive recharge phases **726**"), third channel **730**, a plurality of respective ECAPs **736**A-**736**N (collectively "ECAPs **736**"), and a plurality of stimulation interference signals **738**A-**738**N (collectively "stimulation interference signals **738**"). FIG. **7** may be substantially similar to FIG. **5**B, except for the differences detailed below.

Two or more (e.g. two) control pulses **712** may be delivered during each time event (e.g., window) of a plurality of time events, and each time event represents a time between two consecutive informed pulses **724**. For example, during each time event, a first control pulse may be directly followed by a first respective ECAP, and subsequent to the completion of the first respective ECAP, a second control pulse may be directly followed by a second respective ECAP. Informed pulses may commence following the second respective ECAP. In other examples not illustrated here, three or more control pulses **712** may be delivered, and respective ECAP signals sensed, during each time event of the plurality of time events.

FIG. **8** is a timing diagram **800** illustrating another example of electrical stimulation pulses, respective stimulation signals, and respective ECAPs, in accordance with one or more techniques of this disclosure. For convenience, FIG. **8** is described with reference to IMD **200** of FIG. **2**. As illustrated, timing diagram **800** includes first channel **810**, a plurality of control pulses **812**A-**812**N (collectively "control pulses **812**"), second channel **820**, a plurality of informed pulses **824**A-**824**B (collectively "informed pulses **824**") including passive recharge phases **826**A-**826**B (collectively "passive recharge phases **826**"), third channel **830**, respective ECAPs **836**B (collectively "ECAPs **836**"), and a plurality of stimulation interference signals **838**A-**838**N (collectively "stimulation interference signals **838**"). Timing diagram **800** of FIG. **8** may be substantially the same as timing diagram **700** FIG. **7** except that control pulses **812**A and control pulses **812**N do not evoke ECAPs that are detectible by IMD **200**. Although control pulses **812**B emit ECAPs **836**B, which are detectible by IMD **200**, it may be the case that IMD **200** does not sense enough detectible ECAPs for therapy determination in the example of FIG. **8**.

As such, IMD **200** may determine one or more characteristics of stimulation signals **838** in order to determine one or more parameters of upcoming stimulation pulses following control pulses **812**N.

FIG. **9** is a graph **900** illustrating a stimulation pulse amplitude plot **910** and a stimulation signal amplitude plot **920**, in accordance with one or more techniques of this disclosure. Additionally, graph **900** indicates a first time **922**, a second time **924**, and a third time **926**. FIG. **9** is described with reference to IMD **200** of FIG. **2**.

Stimulation pulse amplitude plot **910** may represent a plot of respective amplitudes of a set of consecutive stimulation pulses delivered by IMD **200**. As seen, if FIG. **9**, each stimulation pulse of the set of stimulation pulses may include a substantially similar amplitude. Stimulation signal amplitude plot **920**, however, indicates a patient event occurring between first time **922** and third time **926** where the amplitudes of responsive stimulation signals increases sharply before settling at a baseline value at third time **926**. In some examples, the patient event may represent a cough, a sneeze, a posture movement, or another action. In any case, the patient event may represent an occurrence between first time **922** and third time **926** in which a distance between one or more of electrodes **232**, **234** of IMD **200** and target tissue (e.g., spinal cord **120**) of patient **105** decreases as compared with a baseline distance. The distance between the one or more of electrodes **232**, **234** of IMD **200** and the target tissue may return to the baseline distance at third time **926**. Second time **924** may indicate a time in which a peak in stimulation signal amplitude occurs.

In some examples, it may be beneficial for processing circuitry **210** to set one or more parameters of stimulation pulses delivered by IMD **200** based on detecting the patient event between first time **922** and third event **926**. In some examples, although not illustrated in FIG. **9**, processing circuitry **210** may decrease an amplitude of one or more therapy pulses delivered by IMD **200** between first time **922** and third time **926** in order to decrease a probability that patient **105** will experience pain or discomfort induced by the stimulation pulses during the patient event. Put another way, the increased amplitudes of stimulation signals in plot **920** indicate that the risk of increased nerve activation and possible discomfort increases due to a likely change in distance between electrodes and nerve fibers.

FIG. **10** is a graph **1000** illustrating a stimulation signal amplitude plot **1020** and an ECAP amplitude plot **1030**, in accordance with one or more techniques of this disclosure. Additionally, graph **1000** includes a region **1022**, a first time **1042**, a second time **1044**, and a third time **1046**. FIG. **10** is described with reference to IMD **200** of FIG. **2**. In some examples, a first patient event may occur between first time **1042** and second time **1044**, a second patient event may occur between second time **1044** and third time **1046**, and a third patient event may occur after third time **1046**. In some examples, processing circuitry **210** may detect one or more signals signal which represent stimulation signal amplitude plot **1020** and one or more signals which represent ECAP amplitude plot **1030**. In some examples, processing circuitry **210** may identify the first patient event, the second patient event, and the third patient event based on one or both of the stimulation signal amplitude plot **1020** and the ECAP amplitude plot **1030**. As seen in FIG. **10**, the amplitude of stimulation signals is generally greater than the amplitude of ECAPs. For this reason, it may be beneficial to determine patient events using the amplitude of stimulation signals which are sensed by IMD **200** in response to delivered stimulation pulses in addition, or as an alternative to, ECAP signals.

Region **1022** may represent a period of time in which patient **105** is sitting still and both of the stimulation signal amplitude plot **1020** and the ECAP amplitude plot **1030** are stable. An amplitude of stimulation pulses delivered by IMD **200** is kept stable throughout the duration of graph **1000**. Each of the first patient event, the second patient event, and the third patient event may represent an aggressor event (e.g., a cough, a sneeze, or a body stretch) which causes a distance between one or more of electrodes **232**, **234** moves closer to spinal cord **120**, causing stimulation pulses to induce a stronger, and sometimes uncomfortable, sensation in patient **105**. As such, it may be beneficial to adjust stimulation in response to detecting an aggressor event such as the first patient event.

FIG. **11** is a timing diagram **1100** illustrating an example of an electrical stimulation pulse **1104** and a respective stimulation signal **1109**, in accordance with one or more techniques of this disclosure. For convenience, FIG. **11** is described with reference to IMD **200** of FIG. **2**. As illustrated, timing diagram **1100** includes stimulation signal **1102** and a sense signal **1106**. In some examples, stimulation signal **1102** includes electrical stimulation pulse **1104** and sense signal includes stimulation signal **1109**. Stimulation signal **1109** includes a first phase **1152**, a second phase **1154**, and a third phase **1156**. Third phase **1156** includes a third phase peak **1158**. The first phase **1152** and second phase **1154** may also include a respective phase peak.

As seen in FIG. **11**, electrical stimulation pulse **1104** may represent a balanced, bi-phasic square pulse that employs an active recharge phase. In other examples not illustrated in FIG. **11**, electrical stimulation pulse **1104** may represent a monophasic pulse that employs a passive recharge phase or an imbalanced bi-phasic pulse that employs a passive recharge phase. Electrical stimulation pulse **1104** includes a negative phase **1112** and a positive phase **1114**. In examples where electrical stimulation pulse **1104** represents a balanced, bi-phasic square pulse, negative phase **1112** and positive phase **1114** may include approximately the same magnitude and approximately the same duration. In some examples, electrical stimulation pulse **1104** may include an interphase interval **1116** between negative phase **1112** and positive phase **1114** to promote propagation of a nerve impulse in response to negative phase **1112** of the bi-phasic pulse. As discussed herein, pulses have different numbers of phases, such as a monophasic or tri-phasic pulse may be employed in other examples.

Stimulation generation circuitry **202** may generate electrical stimulation pulse **1104** based on one of therapy stimulation programs **214** or test stimulation programs **216** and deliver electrical stimulation pulse **1104** to target tissue of patient **105** via any one or combination of electrodes **232**, **234**. Since the one or combination of electrodes **232**, **234** (e.g., "stimulation electrodes") which deliver electrical stimulation pulse **1104** to the target tissue may be located to proximate to a one or combination of electrodes **232**, **234** (e.g., "sensing electrodes") which are configured to sense electrical signals, the sensing electrodes may detect one or more electrical signals emitted by the stimulation electrodes as electrical stimulation pulse **1104**. Sensing circuitry **206** may detect these one or more electrical signals as stimulation signal **1109**. In this way, sensing circuitry **106** may detect stimulation signal **1109** as a direct result of stimulation generation circuitry **202** delivering electrical stimulation pulse **1104** to the target tissue.

Sensing circuitry **206** may sense the first phase **1152** of stimulation signal **1109** in response to stimulation generation circuitry **202** delivering the negative phase **1112** of electrical stimulation pulse **1104**. Additionally, sensing circuitry **206** may sense the second phase **1154** of stimulation signal **1109** in response to stimulation generation circuitry **202** delivering the positive phase **1114** of electrical stimulation pulse **1104**. As seen in FIG. **11**, the first phase **1152** is a positive phase and the second phase **1154** is a negative phase. In this way, sensing circuitry **206** may sense a positive stimulation signal phase in response to stimulation generation circuitry **202** delivering a negative stimulation pulse phase and sensing circuitry **206** may sense a negative stimulation signal phase in response to stimulation generation circuitry **202** delivering a positive stimulation pulse phase, but this is not required. In some examples not illustrated in FIG. **11**, sensing circuitry **206** may sense a positive stimulation signal phase in response to stimulation generation circuitry **202** delivering a positive stimulation pulse phase and sensing circuitry **206** may sense a negative stimulation signal phase in response to stimulation generation circuitry **202** delivering a negative stimulation pulse phase.

In some examples, processing circuitry **210** may determine one or more parameters (e.g., voltage amplitude, current amplitude, pulse duration, pulse shape, or any combination thereof) of upcoming stimulation pulses for generation by stimulation generation circuitry **202** based on one or both of the first phase **1152** and the second phase **1154** of stimulation signal **1109**. Additionally, or alternatively, processing circuitry **210** may determine the one or more parameters of upcoming stimulation pulses for generation by stimulation generation circuitry **202** based on one or more characteristics of third phase **1156** (e.g., an amplitude of peak **1158**). Third phase **1156** may be referred to as a residual phase in some examples and occurs after second phase **1154**. More specifically, third phase **1156** begins after stimulation signal **1109** returns to zero at the conclusion of second phase **1154**. As illustrated, peak **1158** occurs shortly after the conclusion of second phase **1154**. In some examples, a magnitude of peak **1158** of third phase **1156** may be more affected by a posture of patient **105** as compared with a magnitude of first phase **1152** and a magnitude of second phase **1154**. As such, when using the magnitude of peak **1158** to determine therapy, it may be beneficial for processing circuitry **210** to determine a posture of patient **105** based on the acceleration signal generated by acceleration sensor **223**. It is noted that the third phase **1156** may or may not be detectable when an ECAP signal is detectable after stimulation signal **1109**.

FIG. **12** is a timing diagram **1200** illustrating an example of an electrical stimulation pulse **1104**, a respective ECAP **1208**, and a respective stimulation signal **1209**, in accordance with one or more techniques of this disclosure. For convenience, FIG. **12** is described with reference to IMD **200** of FIG. **2**. As illustrated, timing diagram **1200** includes stimulation signal **1202** and a sense signal **1206**. In some examples, stimulation signal **1202** includes electrical stimulation pulse **1204** and sense signal **1206** includes ECAP **1208** and stimulation signal **1209**. Stimulation signal **1209** includes a first phase **1252**, a second phase **1254**, and a third phase **1256**. Third phase **1256** includes a third phase peak **1258**. Third phase **1256** may be referred to as a residual phase in some cases and may represent an ionic rebalancing occurring on one or more of electrodes **232**, **234** of IMD **200**. Although the third phase **1256** may not represent actively delivered charge from IMD **200**, third phase **1256** may still be associated with the first and second phase because the residual charge present in the tissue is due to the pulse that was just delivered. Timing diagram **1200** of FIG. **12** may be substantially the same as timing diagram **1100** of FIG. **11** except that sense signal **1206** includes ECAP **1208** in addition to third phase **1256** of stimulation signal **1209**. ECAP **1208** includes N1 peak **1262** and P2 peak **1264**. As described herein, IMD **200** may adjust one or more parameter values for subsequent stimulation pulses based on characteristics of stimulation signal **1209** and/or ECAP **1208**.

FIG. **13** is a graph illustrating a first transfer function **1310** corresponding to a first posture, a second transfer function **1320** corresponding to a second posture, and a third transfer function **1330** corresponding to a third posture, in accordance with one or more techniques of this disclosure. As described herein, a "transfer function" may represent a curve which establishes a relationship between a first parameter and a second parameter. In the case of FIG. **13**, a transfer function represents a relationship between an amplitude of a stimulation pulse and an expected amplitude of a portion of a stimulation signal that is detected by sensing circuitry **206** in response to delivering the stimulation pulse. In some examples, each transfer function may be used to determine a gain or multiplier that IMD **200** applies to detected stimulation signal amplitudes in order increase or decrease parameter values an appropriate amount (e.g., smaller changes for larger slopes of a transfer function and larger changes for smaller slopes of a transfer function).

First transfer function **1310** may represent a relationship between stimulation pulse amplitude and an expected stimulation signal amplitude while patient **105** is occupying a supine posture. Second transfer function **1320** may represent a relationship between stimulation pulse amplitude and an expected stimulation signal amplitude while patient **105** is occupying a seated posture. Third transfer function **1330** may represent a relationship between stimulation pulse amplitude and an expected stimulation signal amplitude while patient **105** is occupying a standing posture. A prone posture may provide another transfer function that may be different or similar to transfer function **1330** of the standing posture. As seen in FIG. **13**, the relationship between stimulation amplitude and expected stimulation signal amplitude is "steeper" for first transfer function **1310** as compared with second transfer function **1320**. In this way, an increase in stimulation amplitude may cause a first increase in expected stimulation signal amplitude according to first transfer function **1310** and a second increase in expected stimulation signal amplitude according to second transfer function **1320**, where the first increase is greater than the second increase. Additionally, the relationship between stimulation amplitude and expected stimulation signal amplitude is steeper for second transfer function **1320** as compared with third transfer function **1330**.

As discussed in more detail below, processing circuitry **210** of IMD **200** may select, based on a determined posture of patient **105**, a transfer function for identifying an expected amplitude for a stimulation signal sensed by IMD **200** in response to a delivery of a stimulation pulse. The selected transfer function may include first transfer function **1310**, second transfer function **1320**, third transfer function **1330**, or another transfer function not illustrated in FIG. **13**. A set of transfer functions each corresponding top a respective patient posture may be stored by storage device **212** of IMD **200**. Subsequent to selecting a transfer function, processing circuitry may determine the expected amplitude of the stimulation signal based on an amplitude of the respective

stimulation pulse. In some examples, processing circuitry **210** may determine whether to change one or more parameters of upcoming stimulation pulses based on whether a measured amplitude of a stimulation signal falls outside a range of amplitude values, where the range includes the expected amplitude of the stimulation signal.

In some examples, IMD **200** may determine first transfer function **1310**, second transfer function **1320**, and third transfer function **1330** based on characteristics of one or more stimulation signals sensed by IMD **200**. For example, IMD **200** may calculate first transfer function **1310** based on respective amplitude values of a set of stimulation signals detected by IMD **200** while patient **105** is occupying the supine posture. Additionally, IMD **200** may calculate second transfer function **1320** based on respective amplitude values of a set of stimulation signals detected by IMD **200** while patient **105** is occupying the seated posture, and IMD **200** may calculate third transfer function **1330** based on respective amplitude values of a set of stimulation signals detected by IMD **200** while patient **105** is occupying the standing posture. Additionally, or alternatively, IMD **200** may determine first transfer function **1310**, second transfer function **1320**, and third transfer function **1330** based on characteristics of stimulation signals detected in other patients.

FIG. **14** is a graph illustrating a target range of amplitude values for a stimulation signal in relation to a transfer function **1410** corresponding to a respective patient posture, in accordance with one or more techniques of this disclosure. In some examples, transfer function **1410** may represent first transfer function **1310**, second transfer function **1320**, third transfer function **1330**, or another transfer function not illustrated in FIG. **13**. In some examples, a lower boundary function **1412** and an upper boundary function **1414** may define an expected range of stimulation signal amplitudes based on an amplitude of the respective stimulation pulse delivered by stimulation generation circuitry **202**. For example, stimulation pulse amplitude **1420** may correspond to a range of expected stimulation signal amplitude values ranging from lower-bound target stimulation signal amplitude **1422** to upper-bound target stimulation signal amplitude **1424**.

Using an acceleration signal generated by acceleration sensor **223** of IMD **200**, processing circuitry **210** may determine a posture of patient **105**. Additionally, in some cases, processing circuitry **210** may acquire an amplitude of a stimulation pulse and select a transfer function associated with the determined patient posture in order to compute a target estimated stimulation signal amplitude. In some examples, the upper boundary function **1414** and the lower boundary function **1412** may be established based on information representing user input received from external programmer **150**. In some examples, the upper and lower boundary functions **1414** and **1412** may be determined as a tolerance from the target value of transfer function **1410**. However, upper and lower boundary functions **1414** and **1412** may deviate from transfer function **1410** by unequal amounts in other examples.

A stimulation pulse delivered by IMD **200** while patient **105** is occupying a given posture may have a stimulation pulse amplitude. If the responsive stimulation signal amplitude is above the upper-bound target stimulation signal amplitude, processing circuitry **210** may decrease a stimulation pulse amplitude of future stimulation pulses until a responsive stimulation signal includes an amplitude within the target range of stimulation signal amplitudes. If the responsive stimulation signal amplitude is lower than the lower-bound target stimulation signal amplitude, processing circuitry **210** may increase a stimulation pulse amplitude of future stimulation pulses until a responsive stimulation signal includes an amplitude within the target range of stimulation signal amplitudes. If the amplitude of a stimulation signal is within the target range of amplitudes, processing circuitry **210** may hold the amplitude of stimulation pulses constant. In some examples in which processing circuitry **210** detects a shift in posture of patient **105**, processing circuitry **210** may accordingly adjust an amplitude of subsequent stimulation pulses.

As described above, processing circuitry **210** may be configured to set, based on one or more characteristics of a stimulation signal, one or more parameters (e.g., pulse amplitude, pulse duration, and pulse shape) of stimulation pulses following the respective stimulation signal. One way in which processing circuitry **210** may set the one or more parameters of the stimulation pulses includes adjusting an amplitude of a set of stimulation pulses following the respective stimulation signal by a predetermined amplitude value. For example, processing circuitry **210** may determine, based on the acceleration signal generated by the acceleration sensor **223**, a posture of the patient and determine an amplitude of a stimulation pulse delivered by IMD **200**. Processing circuitry **210** may select a transfer function from storage device **212** based on the determined posture, and determine a target range of amplitudes for a stimulation signal corresponding to the stimulation pulse based on the amplitude of the stimulation pulse and the selected transfer function.

In some examples, IMD **200** may change an amplitude of stimulation pulses delivered by IMD **200** based on determining that an amplitude of a stimulation signal is outside of a target range of stimulation signal amplitudes. For example, if an amplitude of a stimulation signal is above an upper bound of the target range of stimulation signal amplitudes, processing circuitry **210** may decrement an amplitude of stimulation pulses until processing circuitry **210** identifies a stimulation signal having an amplitude within the target range of stimulation signal amplitudes. Additionally, or alternatively, if an amplitude of a stimulation signal is below a lower bound of the target range of stimulation signal amplitudes, processing circuitry **210** may increment an amplitude of stimulation pulses until processing circuitry **210** identifies a stimulation signal having an amplitude within the target range of stimulation signal amplitudes. Responsive to identifying a stimulation signal having an amplitude within the target range of stimulation signal amplitudes following a period in which stimulation signal amplitudes are outside of the target range, processing circuitry **210** may restore an amplitude of stimulation pulses delivered by processing circuitry **210** to a baseline value.

In some examples, processing circuitry **210** may determine whether an amplitude of the stimulation signal sensed by IMD **200** in response to the stimulation pulse is within the target range of amplitudes. If the amplitude of the stimulation signal is greater than an upper-bound of target range, processing circuitry **210** may set an amplitude of one or more stimulation pulses following the stimulation signal to a first fall back amplitude. For example, an amplitude transition of consecutive stimulation signals from within the target range to being greater than an upper-bound of the target range may trigger processing circuitry **210** to transition an amplitude of stimulation pulses from a target stimulation pulse amplitude to the first fall back amplitude. In some examples, the first fall back amplitude is lower than the target stimulation pulse amplitude. For example, pro-

cessing circuitry **210** may calculate the first fall back amplitude using the following equation 1.

$$\text{first fall back amplitude} = \text{target stimulation pulse amplitude} - [x] \quad (1)$$

The value "[x]" may be saved by storage device **212** of IMD **200**. In some examples, processing circuitry **210** may save the value "[x]" to storage device **212** based on information received by IMD **200** via communication circuitry **208**. In some examples, processing circuitry **210** may adjust the target stimulation pulse amplitude like based on information indicative of a user input to an external device (e.g., external programmer **150**), and processing circuitry **210** may automatically calculate the first fall back amplitude based on equation 1. In some examples, processing circuitry **210** may maintain an amplitude of stimulation pulses delivered by processing circuitry **210** at the first fall back amplitude until processing circuitry **210** identifies a stimulation signal having an amplitude within the target range. In response to detecting the stimulation signal having an amplitude within the target range, processing circuitry **210** may restore the amplitude of stimulation pulses delivered by IMD **200** to the target stimulation pulse amplitude.

Additionally, in some examples, processing circuitry **210** may determine whether an amplitude of a stimulation signal is less than a lower-bound of a target range of stimulation signal amplitude values, processing circuitry **210** may set an amplitude of one or more stimulation pulses following the stimulation signal to a second fall back amplitude. For example, an amplitude transition of consecutive stimulation signals from being within the target range to being greater than an upper-bound of the target range may trigger processing circuitry **210** to transition an amplitude of stimulation pulses from a target stimulation pulse amplitude to the second fall back amplitude. In some examples, the second fall back amplitude is greater than the target stimulation pulse amplitude. For example, processing circuitry **210** may calculate the second fall back amplitude using the following equation 2.

$$\text{second fall back amplitude} = \text{target stimulation pulse amplitude} - [y] \quad (2)$$

The value "[y]" may be saved by storage device **212** of IMD **200**. In some examples, processing circuitry **210** may save the value "[y]" to storage device **212** based on information received by IMD **200** via communication circuitry **208**. The value "[y]" may be a negative value. In some examples, processing circuitry **210** may adjust the target stimulation pulse amplitude like based on information indicative of a user input to an external device (e.g., external programmer **150**), and processing circuitry **210** may automatically calculate the second fall back amplitude based on equation 2. In some examples, processing circuitry **210** may maintain an amplitude of stimulation pulses delivered by processing circuitry **210** at the second fall back amplitude until processing circuitry **210** identifies a stimulation signal having an amplitude within the target range. In response to detecting the stimulation signal having an amplitude within the target range, processing circuitry **210** may restore the amplitude of stimulation pulses delivered by IMD **200** to the target stimulation pulse amplitude.

FIG. **15** is a graph illustrating target maximum values for a stimulation signal in relation to a transfer function **1510** corresponding to a respective patient posture, in accordance with one or more techniques of this disclosure. In some examples, transfer function **1510** may represent first transfer function **1310**, second transfer function **1320**, third transfer function **1330**, or another transfer function not illustrated in FIG. **13**. In some examples, an upper boundary function **1514** may define a target maximum stimulation signal amplitude value based on an amplitude of the respective stimulation pulse delivered by stimulation generation circuitry **202**. For example, stimulation pulse amplitude **1520** may correspond to a target maximum stimulation signal amplitude value **1524**. In the example of FIG. **15**, the target range may correspond to the values less than upper boundary function **1514**.

In one example, IMD **200** delivers a stimulation pulse at stimulation pulse amplitude **1520**. If a resulting stimulation signal amplitude is greater than target maximum stimulation signal amplitude value **1524**, IMD **200** may decrease the stimulation amplitude of one or more subsequent stimulation pulses until a stimulation pulse causes IMD **200** to sense a stimulation signal defining a stimulation signal amplitude value that is less than a respective target maximum stimulation signal amplitude value. If the stimulation signal amplitude value is less than the respective target maximum stimulation signal amplitude value, IMD **200** may hold the stimulation amplitude until a posture of patient **105** is shifted and IMD **200** may adjust a stimulation amplitude based on identifying a new transfer function associated with the shifted posture.

In some examples, processing circuitry **210** may determine whether an amplitude of a stimulation signal sensed by IMD **200** in response to a stimulation pulse is greater than a target maximum stimulation signal amplitude value of upper boundary function **1514**. If the amplitude of the stimulation signal is greater than the target maximum stimulation signal amplitude value, processing circuitry **210** may set an amplitude of one or more stimulation pulses following the stimulation signal to a fall back amplitude. For example, an amplitude transition of consecutive stimulation signals from being less than the target maximum stimulation signal amplitude value to being greater than the target maximum stimulation signal amplitude value may trigger processing circuitry **210** to decrease an amplitude of stimulation pulses from a target stimulation pulse amplitude to the fall back amplitude. In some examples, the fall back amplitude is lower than the target stimulation pulse amplitude. For example, processing circuitry **210** may calculate the fall back amplitude using the following equation 3.

$$\text{fall back amplitude} = \text{target stimulation pulse amplitude} - [z] \quad (3)$$

The value "[z]" may be saved by storage device **212** of IMD **200**. In some examples, processing circuitry **210** may save the value "[z]" to storage device **212** based on information received by IMD **200** via communication circuitry **208**. In some examples, processing circuitry **210** may adjust the target stimulation pulse amplitude based on information indicative of a user input to an external device (e.g., external programmer **150**), and processing circuitry **210** may automatically calculate the fall back amplitude based on equation 3. In some examples, processing circuitry **210** may maintain an amplitude of stimulation pulses delivered by processing circuitry **210** at the fall back amplitude until processing circuitry **210** identifies a stimulation signal having an amplitude between the respective stimulation signal value of transfer function **1520** and the target maximum stimulation signal amplitude value of upper boundary **1514**. In response to detecting the stimulation signal having an amplitude between the respective stimulation signal value of transfer function **1520** and the target maximum stimulation signal amplitude value of upper boundary **1514**, processing

circuitry **210** may restore the amplitude of stimulation pulses delivered by IMD **200** to the target stimulation pulse amplitude.

FIG. **16** is a flow diagram illustrating an example operation for controlling simulation based on one or more stimulation signals, in accordance with one or more techniques of this disclosure. FIG. **16** is described with respect to IMD **200** of FIG. **2**. However, the techniques of FIG. **16** may be performed by different components of IMD **200** or by additional or alternative medical devices. The technique of FIG. **15** may be similar to the example of FIG. **14** in some examples.

Stimulation generation circuitry **202** is configured to generate a stimulation pulse for delivery to target tissue of patient **105** (**1602**). In some examples, stimulation generation circuitry **202** is configured to generate the stimulation pulse according to therapy stimulation programs **214** and/or test stimulation programs **216** as a one of a set of stimulation pulses. In some examples, therapy stimulation programs **214** and/or test stimulation programs **216** may include one or more parameter values which define stimulation pulses delivered by IMD **200**. Sensing circuitry **206** may sense a stimulation signal responsive to the stimulation pulse delivered to the target tissue of patient **105** (**1604**). In some examples, the stimulation signal may include one or more phases (e.g., a first phase, a second phase, and a third phase). In some examples, a first phase of the stimulation signal may be responsive to a first phase of the stimulation pulse and a second phase of the stimulation signal may be responsive to a second phase of the stimulation pulse. In some examples, a third phase of the stimulation signal may directly follow the second phase of the stimulation signal and the third phase of the stimulation signal may include information indicative of an efficacy of electrical stimulation therapy which includes the stimulation pulse.

Processing circuitry **210** may determine an amplitude associated with the stimulation signal (**1606**). The amplitude may be a characteristic of the stimulation signal. In some examples, the amplitude may represent an amplitude of the third phase of the stimulation signal. In some examples, the amplitude may represent an amplitude of one or both of the first phase of the stimulation signal and the second phase of the stimulation signal. Processing circuitry **210** may determine whether the amplitude associated with the stimulation signal is within a target range of stimulation signal amplitude values (**1608**). In some examples, processing circuitry **210** may select the target range of stimulation signal amplitude values from target values **218** stored in storage device **212**. For example, processing circuitry **210** may select the target range of stimulation signal amplitude values based on a determined posture of patient **105** and an amplitude of the stimulation pulse which causes IMD **200** to sense the stimulation signal. In response to determining that the amplitude associated with the stimulation signal is within the target range of stimulation signal amplitude values ("YES" branch of block **1608**), processing circuitry **210** may maintain one or more parameters of an upcoming one or more stimulation pulses (**1610**) and the example operation may return to block **1602**. In response to determining that the amplitude associated with the stimulation signal is not within the target range of stimulation signal amplitude values ("NO" branch of block **1608**), processing circuitry **210** may change one or more parameters of an upcoming one or more stimulation pulses (**1612**) and the example operation may return to block **1602**.

FIG. **17** is a flow diagram illustrating another example operation for controlling simulation based on one or more stimulation signals, in accordance with one or more techniques of this disclosure. FIG. **17** is described with respect to IMD **200** of FIG. **2**. However, the techniques of FIG. **17** may be performed by different components of IMD **200** or by additional or alternative medical devices. The technique of FIG. **17** may be similar to the example of FIG. **15**.

Stimulation generation circuitry **202** is configured to generate a stimulation pulse for delivery to target tissue of patient **105** (**1702**). In some examples, stimulation generation circuitry **202** is configured to generate the stimulation pulse according to therapy stimulation programs **214** and/or test stimulation programs **216** as a one of a set of stimulation pulses. In some examples, therapy stimulation programs **214** and/or test stimulation programs **216** may include one or more parameter values which define stimulation pulses delivered by IMD **200**. Sensing circuitry **206** may sense a stimulation signal responsive to the stimulation pulse delivered to the target tissue of patient **105** (**1704**). In some examples, the stimulation signal may include one or more phases (e.g., a first phase, a second phase, and a third phase). In some examples, a first phase of the stimulation signal may be responsive to a first phase of the stimulation pulse and a second phase of the stimulation signal may be responsive to a second phase of the stimulation pulse. In some examples, a third phase of the stimulation signal may directly follow the second phase of the stimulation signal and the third phase of the stimulation signal may include information indicative of an efficacy of electrical stimulation therapy which includes the stimulation pulse.

Processing circuitry **210** may determine an amplitude associated with the stimulation signal (**1706**). The amplitude may be a characteristic of the stimulation signal. In some examples, the amplitude may represent an amplitude of the third phase of the stimulation signal. In some examples, the amplitude may represent an amplitude of one or both of the first phase of the stimulation signal and the second phase of the stimulation signal. Processing circuitry **210** may determine whether the amplitude associated with the stimulation signal is greater than a target maximum stimulation signal amplitude value (**1708**). In some examples, processing circuitry **210** may select the target maximum stimulation signal amplitude value from target values **218** stored in storage device **212**. For example, processing circuitry **210** may select the target maximum stimulation signal amplitude value based on a determined posture of patient **105** and an amplitude of the stimulation pulse which causes IMD **200** to sense the stimulation signal. In response to determining that the amplitude associated with the stimulation signal is not greater than the target maximum stimulation signal amplitude value ("NO" branch of block **1708**), processing circuitry **210** may maintain one or more parameters of an upcoming one or more stimulation pulses (**1710**) and the example operation may return to block **1702**. In response to determining that the amplitude associated with the stimulation signal is greater than the target maximum stimulation signal amplitude value ("YES" branch of block **1708**), processing circuitry **210** may decrease one or more parameters of an upcoming one or more stimulation pulses (**1712**) and the example operation may return to block **1702**.

FIG. **18** is a flow diagram illustrating another example operation for controlling simulation based on one or more stimulation signals, in accordance with one or more techniques of this disclosure. FIG. **18** is described with respect to IMD **200** of FIG. **2**. However, the techniques of FIG. **18** may be performed by different components of IMD **200** or by additional or alternative medical devices.

Processing circuitry **210** may determine an amplitude associated with a stimulation signal responsive to a stimulation pulse (**1802**) delivered by IMD **200**. The amplitude may be a characteristic of the stimulation signal. In some examples, the amplitude may represent an amplitude of the third phase of the stimulation signal. In some examples, the amplitude may represent an amplitude of one or both of the first phase of the stimulation signal and the second phase of the stimulation signal. Processing circuitry **210** may determine whether the amplitude associated with the stimulation signal is greater than a target maximum stimulation signal amplitude value (**1804**). In some examples, processing circuitry **210** may select the target maximum stimulation signal amplitude value from target values **218** stored in storage device **212**. For example, processing circuitry **210** may select the target maximum stimulation signal amplitude value based on a determined posture of patient **105** and an amplitude of the stimulation pulse which causes IMD **200** to sense the stimulation signal.

In response to determining that the amplitude associated with the stimulation signal is greater than the target maximum stimulation signal amplitude value ("YES" branch of block **1804**), processing circuitry **210** may determine whether a current stimulation pulse amplitude represents a fallback stimulation pulse amplitude (**1806**). In some examples, the fallback stimulation amplitude may be calculated according to equation 3. If the current stimulation pulse amplitude represents the fallback stimulation pulse amplitude ("YES" branch of block **1806**), processing circuitry **210** maintains an amplitude of one or more upcoming stimulation pulses at the fallback stimulation amplitude (**1808**) and the example operation returns to block **1802**. If the current stimulation pulse amplitude does not represent the fallback stimulation pulse amplitude ("NO" branch of block **1806**), processing circuitry **210** may set the amplitude of one or more upcoming stimulation pulses at the fallback stimulation amplitude (**1810**) and the example operation returns to block **1802**.

In response to determining that the amplitude associated with the stimulation signal is not greater than the target maximum stimulation signal amplitude value ("NO" branch of block **1804**), processing circuitry **210** may determine whether a current stimulation pulse amplitude represents a fallback stimulation pulse amplitude (**1812**). In some examples, the fallback stimulation amplitude may be calculated according to equation 3. If the current stimulation pulse amplitude represents the fallback stimulation pulse amplitude ("YES" branch of block **1812**), processing circuitry **210** maintains an amplitude of one or more upcoming stimulation pulses at the fallback stimulation amplitude (**1814**) and the example operation returns to block **1802**. If the current stimulation pulse amplitude does not represent the fallback stimulation pulse amplitude ("NO" branch of block **1812**), processing circuitry **210** may restore the amplitude of one or more upcoming stimulation pulses to a baseline stimulation amplitude (**1816**) and the example operation returns to block **1802**. In some examples, the baseline stimulation amplitude represents the target stimulation pulse amplitude of equation 3.

FIG. **19** is a flow diagram illustrating another example operation for controlling simulation based on one or more stimulation signals, in accordance with one or more techniques of this disclosure. FIG. **19** is described with respect to IMD **200** of FIG. **2**. However, the techniques of FIG. **19** may be performed by different components of IMD **200** or by additional or alternative medical devices.

Processing circuitry **210** may determine an amplitude associated with a stimulation signal responsive to a stimulation pulse (**1902**) delivered by IMD **200**. The amplitude may be a characteristic of the stimulation signal. In some examples, the amplitude may represent an amplitude of the third phase of the stimulation signal. In some examples, the amplitude may represent an amplitude of one or both of the first phase of the stimulation signal and the second phase of the stimulation signal. Processing circuitry **210** may determine whether the amplitude associated with the stimulation signal is outside of a target range of stimulation signal amplitude values which extends from a lower bound amplitude value to an upper bound amplitude value (**1904**). In some examples, processing circuitry **210** may select the target range from target values **218** stored in storage device **212**. For example, processing circuitry **210** may select the target range based on a determined posture of patient **105** and an amplitude of the stimulation pulse which causes IMD **200** to sense the stimulation signal.

In response to determining that the amplitude associated with the stimulation signal is outside of the target range ("YES" branch of block **1904**), processing circuitry **210** may determine whether a current stimulation pulse amplitude represents a first fallback stimulation pulse amplitude or a second fallback stimulation pulse amplitude (**1906**). For example, if processing circuitry **210** determines that the amplitude associated with the stimulation signal is greater than the upper bound of the target range, processing circuitry **210** may determine whether a current stimulation pulse amplitude represents the first fallback amplitude (e.g., calculated using equation 1) and if processing circuitry **210** determines that the amplitude associated with the stimulation signal is less than the lower bound of the target range, processing circuitry **210** may determine whether a current stimulation pulse amplitude represents the second fallback amplitude (e.g., calculated using equation 2).

If the current stimulation pulse amplitude represents the first fallback stimulation pulse amplitude or the second fallback stimulation pulse amplitude ("YES" branch of block **1906**), processing circuitry **210** maintains an amplitude of one or more upcoming stimulation pulses at the respective first or second fallback stimulation amplitude (**1908**) and the example operation returns to block **1902**. If the current stimulation pulse amplitude does not represent the respective first or second fallback stimulation pulse amplitude ("NO" branch of block **1906**), processing circuitry **210** may set the amplitude of one or more upcoming stimulation pulses at the respective one of the first fallback stimulation amplitude or the second fallback stimulation amplitude (**1910**) and the example operation returns to block **1902**. For example, if processing circuitry **210** determines that the amplitude associated with the stimulation signal is greater than the upper bound of the target range, processing circuitry **210** may set the amplitude of one or more upcoming stimulation pulses at the first fallback stimulation pulse amplitude and if processing circuitry **210** determines that the amplitude associated with the stimulation signal is less than the lower bound of the target range, processing circuitry **210** may set the amplitude of one or more upcoming stimulation pulses at the second fallback stimulation pulse amplitude.

In response to determining that the amplitude associated with the stimulation signal is not outside of the target range ("NO" branch of block **1904**), processing circuitry **210** may determine whether a current stimulation pulse amplitude represents the first fallback stimulation pulse amplitude or the second fallback stimulation pulse amplitude (**1912**). If the current stimulation pulse amplitude represents the first

fallback stimulation pulse amplitude or the second fallback stimulation pulse amplitude ("YES" branch of block **1912**), processing circuitry **210** maintains an amplitude of one or more upcoming stimulation pulses at the respective first or second fallback stimulation amplitude (**1914**) and the example operation returns to block **1902**. If the current stimulation pulse amplitude does not represent the first fallback stimulation pulse amplitude or the second fallback stimulation pulse amplitude ("NO" branch of block **1912**), processing circuitry **210** may restore the amplitude of one or more upcoming stimulation pulses to a baseline stimulation amplitude (**1916**) and the example operation returns to block **1902**. In some examples, the baseline stimulation amplitude represents the target stimulation pulse amplitude of equation 1 and equation 2.

The following examples are example systems, devices, and methods described herein.

Example 1: A medical device comprising: stimulation generation circuitry configured to deliver a first stimulation pulse to a patient; sensing circuitry configured to sense the first stimulation pulse; and processing circuitry configured to: determine that a value of a characteristic of the sensed first stimulation pulse exceeds a target stimulation pulse value; and responsive to determining that the value of the characteristic of the sensed first stimulation pulse exceeds the target stimulation pulse value, change a first value of a parameter to a second value of the parameter that at least partially defines a second stimulation pulse deliverable by the stimulation generation circuitry after the first stimulation pulse was sensed.

Example 2: The medical device of example 1, wherein to determine that the value of the characteristic of the sensed first stimulation pulse exceeds the target stimulation pulse value, the processing circuitry is configured to: determine that the value of the characteristic of the sensed first stimulation pulse is greater than a target maximum stimulation pulse characteristic value, and wherein to change the first value of the parameter to the second value of the parameter, the processing circuitry is configured to: decrease the first value of the parameter to the second value of the parameter, the second value of the parameter at least partially defining the second stimulation pulse.

Example 3: The medical device of example 2, wherein to decrease the first value of the parameter to the second value of the parameter that at least partially defines the second stimulation pulse, the processing circuitry is configured to: set the parameter which at least partially defines the second stimulation pulse to a fallback parameter value that at least partially defines the second stimulation pulse, wherein the processing circuitry is further configured to: sense a third stimulation pulse following the second stimulation pulse; and responsive to determining that a value of a characteristic of the sensed third stimulation pulse does not exceed the target stimulation pulse value, restore the parameter that at least partially defines a fourth stimulation pulse deliverable by the stimulation generation circuitry to the first value of the parameter.

Example 4: The medical device of any of examples 2-3, wherein the processing circuitry is further configured to: determine that the value of the characteristic of the sensed first stimulation pulse is less than a target minimum stimulation pulse characteristic value, wherein a target range of stimulation pulse characteristic values extend from the target minimum stimulation pulse characteristic value to the target maximum stimulation pulse characteristic value; and responsive to determining that the value of the characteristic of the sensed first stimulation pulse is less than the target minimum stimulation pulse characteristic value, increase the first value of the parameter to the second value of the parameter that at least partially defines the second stimulation pulse.

Example 5: The medical device of any of examples 1-4, wherein the stimulation generation circuitry is configured to deliver a plurality of stimulation pulses including the first stimulation pulse and the second stimulation pulse, and wherein the sensing circuitry is further configured to: detect a plurality of evoked compound action potentials (ECAPs), wherein each ECAP of the plurality of ECAPs is elicited by a respective pulse of the plurality of pulses, and wherein the number of ECAPs of the plurality of ECAPs is lower than a number of stimulation pulses of the plurality of stimulation pulses.

Example 6: The medical device of example 5, wherein the processing circuitry is further configured to determine whether the plurality of stimulation pulses elicit greater than a threshold ratio of detectable ECAPs per stimulation pulse.

Example 7: The medical device of example 6, wherein to determine whether the plurality of stimulation pulses elicit greater than the threshold ratio of detectable ECAPs per stimulation pulse, the processing circuitry is configured to: identify a set of ECAPs elicited by a sequence of consecutive stimulation pulses of the plurality of stimulation pulses; calculate a ratio of a number of the set of ECAPs to a number of the sequence of consecutive stimulation pulses; and determine whether the ratio is greater than the threshold ratio.

Example 8: The medical device of any of examples 6-7, wherein the processing circuitry is further configured to: responsive to determining that the plurality of stimulation pulses elicit greater than the threshold ratio of detectible ECAPs: change, based on the value of the characteristic of the sensed first stimulation pulse and a value of a characteristic of an ECAP corresponding to the first stimulation pulse, the value of the parameter that at least partially defines the second stimulation pulse.

Example 9: The medical device of any of examples 6-8, wherein the processing circuitry is further configured to: responsive to determining that the plurality of stimulation pulses does not elicit greater than the threshold ratio of detectible ECAPs: change, based on the value of the characteristic of the first stimulation pulse and not based on a value of a characteristic of an ECAP corresponding to the first stimulation pulse, the value of the parameter that at least partially defines the second stimulation pulse.

Example 10: The medical device of examples 1-9, further comprising: an accelerometer configured to generate an accelerometer signal, wherein the processing circuitry is further configured to: identify, based on the accelerometer signal, a posture of a set of postures which the patient is occupying; identify an amplitude of the first stimulation pulse; and select, based on the identified posture and the amplitude of the first stimulation pulse, the target stimulation pulse value from a set of target stimulation pulse values, wherein each target stimulation pulse value of the set of target stimulation pulse values corresponds to a respective posture of the set of postures and a respective amplitude of the first stimulation pulse.

Example 11: The medical device of examples 1-10, wherein the medical device comprises an implantable medical device, and wherein the implantable medical device comprises the stimulation generation circuitry, the sensing circuitry, and the processing circuitry.

Example 12: The medical device of any of examples 1-11, wherein the first value of the parameter at least partially defines the first stimulation pulse.

Example 13: The medical device of any of examples 1-12, wherein the first stimulation pulse represents a control pulse of a set of control pulses, wherein the second stimulation pulse represents an informed pulse of a set of informed pulses, wherein the first value of the parameter at least partially defines a pervious informed pulse of the set of informed pulses.

Example 14: The medical device of any of examples 1-13, wherein the stimulation generation circuitry is configured to deliver at least one stimulation pulse between a time in which the stimulation generation circuitry delivers the first stimulation pulse and a time in which the stimulation generation circuitry delivers the second stimulation pulse.

Example 15: The medical device of any of examples 1-14, wherein the first stimulation pulse is one of a first set of one or more stimulation pulses, wherein the second stimulation pulse is one of a second set of one or more stimulation pulses, wherein the characteristic of the sensed first stimulation pulse represents a characteristic of the sensed first set of one or more stimulation pulses, and wherein the processing circuitry is configured to calculate the characteristic of the sensed first set of one or more stimulation pulses based on respective characteristic values of each stimulation pulse of the first set of one or more stimulation pulses.

Example 16: A method comprising: delivering, by stimulation generation circuitry, a first stimulation pulse to a patient; sensing, by sensing circuitry, the first stimulation pulse; determining, by processing circuitry, that a value of a characteristic of the sensed first stimulation pulse exceeds a target stimulation pulse value; and responsive to determining that the value of the characteristic of the sensed first stimulation pulse exceeds the target stimulation pulse value, changing, by the processing circuitry, a first value of a parameter to a second value of the parameter that at least partially defines a second stimulation pulse deliverable by the stimulation generation circuitry after the first stimulation pulse was sensed.

Example 17: The method of example 16, wherein determining that the value of the characteristic of the sensed first stimulation pulse exceeds the target stimulation pulse value comprises: determining that the value of the characteristic of the sensed first stimulation pulse is greater than a target maximum stimulation pulse characteristic value, and wherein changing the first value of the parameter to the second value of the parameter comprises: decreasing the first value of the parameter to the second value of the parameter, the second value of the parameter at least partially defining the second stimulation pulse.

Example 18: The method of example 17, wherein decreasing the first value of the parameter to the second value of the parameter that at least partially defines the second stimulation pulse comprises: setting the parameter which at least partially defines the second stimulation pulse to a fallback parameter value that at least partially defines the second stimulation pulse, wherein the method further comprises: sensing a third stimulation pulse following the second stimulation pulse; and responsive to determining that a value of a characteristic of the sensed third stimulation pulse does not exceed the target stimulation pulse value, restoring the parameter that at least partially defines a fourth stimulation pulse deliverable by the stimulation generation circuitry to the first value of the parameter.

Example 19: The method of examples 17-18, further comprising: determining, by the processing circuitry, that the value of the characteristic of the sensed first stimulation pulse is less than a target minimum stimulation pulse characteristic value, wherein a target range of stimulation pulse characteristic values extend from the target minimum stimulation pulse characteristic value to the target maximum stimulation pulse characteristic value; and responsive to determining that the value of the characteristic of the sensed first stimulation pulse is less than the target minimum stimulation pulse characteristic value, increasing the first value of the parameter to the second value of the parameter that at least partially defines the second stimulation pulse.

Example 20: The method of examples 16-19, further comprising: delivering, by the stimulation generation circuitry, a plurality of stimulation pulses including the first stimulation pulse and the second stimulation pulse; and detecting, by the sensing circuitry, a plurality of evoked compound action potentials (ECAPs), wherein each ECAP of the plurality of ECAPs is elicited by a respective pulse of the plurality of pulses, and wherein the number of ECAPs of the plurality of ECAPs is lower than a number of stimulation pulses of the plurality of stimulation pulses.

Example 21: The method of examples 16-20, further comprising: generating, by an accelerometer, an accelerometer signal; identifying, by the processing circuitry based on the accelerometer signal, a posture of a set of postures which the patient is occupying; identifying, by the processing circuitry, an amplitude of the first stimulation pulse; and selecting, by the processing circuitry based on the identified posture and the amplitude of the first stimulation pulse, the target stimulation pulse value from a set of target stimulation pulse values, wherein each target stimulation pulse value of the set of target stimulation pulse values corresponds to a respective posture of the set of postures and a respective amplitude of the first stimulation pulse.

Example 22: A medical device comprising: stimulation generation circuitry configured to deliver a first stimulation pulse to a patient; sensing circuitry configured to sense a residual phase of the first stimulation pulse; and processing circuitry configured to: determine that a value of a characteristic of the sensed residual phase of the first stimulation pulse exceeds a target residual phase value; and responsive to determining that the value of the characteristic of the sensed residual phase exceeds the target residual phase value, change a first value of a parameter to a second value of the parameter that at least partially defines a second stimulation pulse deliverable by the stimulation generation circuitry after the residual phase of the first stimulation pulse was sensed.

Example 23: The medical device of example 22, wherein the stimulation generation circuitry is configured to deliver a plurality of stimulation pulses including the first stimulation pulse and the second stimulation pulse, and wherein the sensing circuitry is further configured to: detect a plurality of evoked compound action potentials (ECAPs), wherein each ECAP of the plurality of ECAPs is elicited by a respective pulse of the plurality of pulses, and wherein the number of ECAPs of the plurality of ECAPs is lower than a number of stimulation pulses of the plurality of stimulation pulses.

Example 24: The medical device of example 23, wherein the processing circuitry is further configured to determine whether the plurality of stimulation pulses elicit greater than a threshold ratio of detectable ECAPs per stimulation pulse.

Example 25: The medical device of example 24, wherein to determine whether the plurality of stimulation pulses elicit greater than the threshold ratio of detectable ECAPs per stimulation pulse, the processing circuitry is configured to: identify a set of ECAPs elicited by a sequence of

consecutive stimulation pulses of the plurality of stimulation pulses; calculate a ratio of a number of the set of ECAPs to a number of the sequence of consecutive stimulation pulses; and determine whether the ratio is greater than the threshold ratio.

Example 26: The medical device of claims **24-25**, wherein the processing circuitry is further configured to: responsive to determining that the plurality of stimulation pulses elicit greater than the threshold ratio of detectible ECAPs: change, based on the value of the characteristic of the sensed residual phase of the first stimulation pulse and a value of a characteristic of an ECAP corresponding to the first stimulation pulse, the value of the parameter that at least partially defines the second stimulation pulse.

Example 27: The medical device of claims **24-26**, wherein the processing circuitry is further configured to: responsive to determining that the plurality of stimulation pulses does not elicit greater than the threshold ratio of detectible ECAPs: change, based on the value of the characteristic of the sensed residual phase of the first stimulation pulse and not based on a value of a characteristic of an ECAP corresponding to the first stimulation pulse, the value of the parameter that at least partially defines the second stimulation pulse.

The techniques described in this disclosure may be implemented, at least in part, in hardware, software, firmware, or any combination thereof. For example, various aspects of the techniques may be implemented within one or more microprocessors, DSPs, ASICS, FPGAs, or any other equivalent integrated or discrete logic QRS circuitry, as well as any combinations of such components, embodied in external devices, such as physician or patient programmers, stimulators, or other devices. The terms "processor" and "processing circuitry" may generally refer to any of the foregoing logic circuitry, alone or in combination with other logic circuitry, or any other equivalent circuitry, and alone or in combination with other digital or analog circuitry.

For aspects implemented in software, at least some of the functionality ascribed to the systems and devices described in this disclosure may be embodied as instructions on a computer-readable storage medium such as RAM, DRAM, SRAM, magnetic discs, optical discs, flash memories, or forms of EPROM or EEPROM. The instructions may be executed to support one or more aspects of the functionality described in this disclosure.

In addition, in some aspects, the functionality described herein may be provided within dedicated hardware and/or software modules. Depiction of different features as modules or units is intended to highlight different functional aspects and does not necessarily imply that such modules or units must be realized by separate hardware or software components. Rather, functionality associated with one or more modules or units may be performed by separate hardware or software components or integrated within common or separate hardware or software components. Also, the techniques could be fully implemented in one or more circuits or logic elements. The techniques of this disclosure may be implemented in a wide variety of devices or apparatuses, including an IMD, an external programmer, a combination of an IMD and external programmer, an integrated circuit (IC) or a set of ICs, and/or discrete electrical circuitry, residing in an IMD and/or external programmer.

What is claimed is:

1. A medical device comprising:

stimulation generation circuitry configured to deliver a plurality of stimulation pulses including a first stimulation pulse and a second stimulation pulse to a patient, the first stimulation pulse at least partially defined by a first value of a parameter;

sensing circuitry configured to sense, via an electrode combination, the first stimulation pulse delivered to the patient; and

processing circuitry configured to:

identify a value of a characteristic of the first stimulation pulse sensed via the sensing circuitry and the electrode combination;

determine that the value of a characteristic of the sensed first stimulation pulse exceeds a target stimulation pulse value; and

responsive to determining that the value of the characteristic of the sensed first stimulation pulse exceeds the target stimulation pulse value, change the first value of the parameter to a second value of the parameter that at least partially defines the second stimulation pulse deliverable by the stimulation generation circuitry after the first stimulation pulse was sensed, wherein:

the sensing circuitry is configured to detect a plurality of evoked compound action potentials (ECAPs), each ECAP of the plurality of ECAPs being elicited by a respective pulse of the plurality of stimulation pulses,

the number of ECAPs of the plurality of ECAPs is lower than a number of stimulation pulses of the plurality of stimulation pulses, and

the processing circuitry is configured to determine whether the plurality of stimulation pulses elicit greater than a threshold ratio of detectable ECAPs to stimulation pulses.

2. The medical device of claim **1**, wherein to determine that the value of the characteristic of the sensed first stimulation pulse exceeds the target stimulation pulse value, the processing circuitry is configured to:

determine that the value of the characteristic of the sensed first stimulation pulse is greater than a target maximum stimulation pulse characteristic value, and wherein to change the first value of the parameter to the second value of the parameter, the processing circuitry is configured to:

decrease the first value of the parameter to the second value of the parameter, the second value of the parameter at least partially defining the second stimulation pulse.

3. The medical device of claim **2**, wherein to decrease the first value of the parameter to the second value of the parameter that at least partially defines the second stimulation pulse, the processing circuitry is configured to:

set the parameter which at least partially defines the second stimulation pulse to a fallback parameter value that at least partially defines the second stimulation pulse,

wherein the sensing circuitry is further configured to sense a third stimulation pulse following the second stimulation pulse, and

wherein the processing circuitry is configured to:

identify a value of a characteristic of the third stimulation pulse sensed via the sensing circuitry;

responsive to determining that the value of a characteristic of the sensed third stimulation pulse does not exceed the target stimulation pulse value, restore the parameter that at least partially defines a fourth stimulation pulse deliverable by the stimulation generation circuitry to the first value of the parameter.

4. The medical device of claim 2, wherein the processing circuitry is further configured to:

determine that the value of the characteristic of the sensed first stimulation pulse is less than a target minimum stimulation pulse characteristic value, wherein a target range of stimulation pulse characteristic values extend from the target minimum stimulation pulse characteristic value to the target maximum stimulation pulse characteristic value; and

responsive to determining that the value of the characteristic of the sensed first stimulation pulse is less than the target minimum stimulation pulse characteristic value, increase the first value of the parameter to the second value of the parameter that at least partially defines the second stimulation pulse.

5. The medical device of claim 1, wherein to determine whether the plurality of stimulation pulses elicit greater than the threshold ratio of detectable ECAPs to stimulation pulses, the processing circuitry is configured to:

identify a set of ECAPs elicited by a sequence of consecutive stimulation pulses of the plurality of stimulation pulses;

calculate a ratio of a number of the set of ECAPs to a number of the sequence of consecutive stimulation pulses; and

determine whether the ratio is greater than the threshold ratio.

6. The medical device of claim 1, wherein the processing circuitry is further configured to:

responsive to determining that the plurality of stimulation pulses elicit greater than the threshold ratio of detectible ECAPs:

change, based on the value of the characteristic of the sensed first stimulation pulse and a value of a characteristic of an ECAP corresponding to the first stimulation pulse, the value of the parameter that at least partially defines the second stimulation pulse.

7. The medical device of claim 1, wherein the processing circuitry is further configured to:

responsive to determining that the plurality of stimulation pulses does not elicit greater than the threshold ratio of detectible ECAPs:

change, based on the value of the characteristic of the first stimulation pulse and not based on a value of a characteristic of an ECAP corresponding to the first stimulation pulse, the value of the parameter that at least partially defines the second stimulation pulse.

8. The medical device of claim 1, further comprising:

an accelerometer configured to generate an accelerometer signal, wherein the processing circuitry is further configured to:

identify, based on the accelerometer signal, a posture of a set of postures which the patient is occupying;

identify an amplitude of the first stimulation pulse; and

select, based on the identified posture and the amplitude of the first stimulation pulse, the target stimulation pulse value from a set of target stimulation pulse values, wherein each target stimulation pulse value of the set of target stimulation pulse values corresponds to a respective posture of the set of postures and a respective amplitude of the first stimulation pulse.

9. The medical device of claim 1, wherein the medical device comprises an implantable medical device, and wherein the implantable medical device comprises the stimulation generation circuitry, the sensing circuitry, and the processing circuitry.

10. The medical device of claim 1, wherein the first value of the parameter at least partially defines the first stimulation pulse.

11. The medical device of claim 1, wherein the first stimulation pulse represents a control pulse of a set of control pulses, wherein the second stimulation pulse represents an informed pulse of a set of informed pulses, wherein the first value of the parameter at least partially defines a previous informed pulse of the set of informed pulses.

12. The medical device of claim 1, wherein the stimulation generation circuitry is configured to deliver at least one stimulation pulse between a time in which the stimulation generation circuitry delivers the first stimulation pulse and a time in which the stimulation generation circuitry delivers the second stimulation pulse.

13. The medical device of claim 1, wherein the first stimulation pulse is one of a first set of one or more stimulation pulses, wherein the second stimulation pulse is one of a second set of one or more stimulation pulses, wherein the characteristic of the sensed first stimulation pulse represents a characteristic of the sensed first set of one or more stimulation pulses, and wherein the processing circuitry is configured to calculate the characteristic of the sensed first set of one or more stimulation pulses based on respective characteristic values of each stimulation pulse of the first set of one or more stimulation pulses.

14. A method comprising:

delivering, by stimulation generation circuitry, a first stimulation pulse to a patient, the first stimulation pulse at least partially defined by a first value of a parameter;

sensing, by sensing circuitry and via an electrode combination, the first stimulation pulse delivered to the patient;

identifying, by processing circuitry, a value of a characteristic of the first stimulation pulse sensed via the sensing circuitry and the electrode combination;

determining, by the processing circuitry, that a value of a characteristic of the sensed first stimulation pulse exceeds a target stimulation pulse value;

responsive to determining that the value of the characteristic of the sensed first stimulation pulse exceeds the target stimulation pulse value, changing, by the processing circuitry, the first value of the parameter to a second value of the parameter that at least partially defines a second stimulation pulse deliverable by the stimulation generation circuitry after the first stimulation pulse was sensed;

delivering, by the stimulation generation circuitry, a plurality of stimulation pulses, the plurality of stimulation pulses including the first stimulation pulse and the second stimulation pulse; and

detecting, by the sensing circuitry, a plurality of evoked compound action potentials (ECAPs), each ECAP of the plurality of ECAPs being elicited by a respective pulse of the plurality of stimulation pulses, wherein the number of ECAPs of the plurality of ECAPs is lower than a number of stimulation pulses of the plurality of stimulation pulses; and

determining, by the processing circuitry, whether the plurality of stimulation pulses elicit greater than a threshold ratio of detectable ECAPs to stimulation pulses.

15. The method of claim 14, wherein determining that the value of the characteristic of the sensed first stimulation pulse exceeds the target stimulation pulse value comprises:

determining that the value of the characteristic of the sensed first stimulation pulse is greater than a target

maximum stimulation pulse characteristic value, and wherein changing the first value of the parameter to the second value of the parameter comprises:

decreasing the first value of the parameter to the second value of the parameter, the second value of the parameter at least partially defining the second stimulation pulse.

16. The method of claim **15**, wherein decreasing the first value of the parameter to the second value of the parameter that at least partially defines the second stimulation pulse comprises:

setting the parameter which at least partially defines the second stimulation pulse to a fallback parameter value that at least partially defines the second stimulation pulse, wherein the method further comprises:

sensing, by the sensing circuitry, a third stimulation pulse following the second stimulation pulse;

identifying, by the processing circuitry, a value of a characteristic of the third stimulation pulse sensed via the sensing circuitry; and

responsive to determining that the value of a characteristic of the sensed third stimulation pulse does not exceed the target stimulation pulse value, restoring the parameter that at least partially defines a fourth stimulation pulse deliverable by the stimulation generation circuitry to the first value of the parameter.

17. The method of claim **15**, further comprising:

determining, by the processing circuitry, that the value of the characteristic of the sensed first stimulation pulse is less than a target minimum stimulation pulse characteristic value, wherein a target range of stimulation pulse characteristic values extend from the target minimum stimulation pulse characteristic value to the target maximum stimulation pulse characteristic value; and

responsive to determining that the value of the characteristic of the sensed first stimulation pulse is less than the target minimum stimulation pulse characteristic value, increasing the first value of the parameter to the second value of the parameter that at least partially defines the second stimulation pulse.

18. The method of claim **14**, further comprising:

generating, by an accelerometer, an accelerometer signal;

identifying, by the processing circuitry based on the accelerometer signal, a posture of a set of postures which the patient is occupying;

identifying, by the processing circuitry, an amplitude of the first stimulation pulse; and

selecting, by the processing circuitry based on the identified posture and the amplitude of the first stimulation pulse, the target stimulation pulse value from a set of target stimulation pulse values, wherein each target stimulation pulse value of the set of target stimulation pulse values corresponds to a respective posture of the set of postures and a respective amplitude of the first stimulation pulse.

19. A medical device comprising:

stimulation generation circuitry configured to deliver a first stimulation pulse to a patient, the first stimulation pulse at least partially defined by a first value of a parameter, wherein the first stimulation pulse comprises a first phase and a second phase;

sensing circuitry configured to sense, via an electrode combination, a residual phase of the first stimulation pulse delivered to the patient, the residual phase occurring after the first phase and the second phase; and

processing circuitry configured to:

identify a value of a characteristic of the residual phase of the first stimulation pulse sensed via the sensing circuitry and the electrode combination;

determine that the value of a characteristic of the residual phase of the first stimulation pulse exceeds a target residual phase value; and

responsive to determining that the value of the characteristic of the sensed residual phase exceeds the target residual phase value, change the first value of the parameter to a second value of the parameter that at least partially defines a second stimulation pulse deliverable by the stimulation generation circuitry after the residual phase of the first stimulation pulse was sensed.

20. The medical device of claim **19**, wherein the stimulation generation circuitry is configured to deliver a plurality of stimulation pulses including the first stimulation pulse and the second stimulation pulse, and wherein the sensing circuitry is further configured to:

detect a plurality of evoked compound action potentials (ECAPs), wherein each ECAP of the plurality of ECAPs is elicited by a respective pulse of the plurality of pulses, and wherein the number of ECAPs of the plurality of ECAPs is lower than a number of stimulation pulses of the plurality of stimulation pulses.

21. The medical device of claim **20**, wherein the processing circuitry is further configured to determine whether the plurality of stimulation pulses elicit greater than a threshold ratio of detectable ECAPs to stimulation pulses.

22. The medical device of claim **21**, wherein to determine whether the plurality of stimulation pulses elicit greater than the threshold ratio of detectable ECAPs to stimulation pulses, the processing circuitry is configured to:

identify a set of ECAPs elicited by a sequence of consecutive stimulation pulses of the plurality of stimulation pulses;

calculate a ratio of a number of the set of ECAPs to a number of the sequence of consecutive stimulation pulses; and

determine whether the ratio is greater than the threshold ratio.

23. The medical device of claim **21**, wherein the processing circuitry is further configured to:

responsive to determining that the plurality of stimulation pulses elicit greater than the threshold ratio of detectible ECAPs:

change, based on the value of the characteristic of the sensed residual phase of the first stimulation pulse and a value of a characteristic of an ECAP corresponding to the first stimulation pulse, the value of the parameter that at least partially defines the second stimulation pulse.

24. The medical device of claim **21**, wherein the processing circuitry is further configured to:

responsive to determining that the plurality of stimulation pulses does not elicit greater than the threshold ratio of detectible ECAPs:

change, based on the value of the characteristic of the sensed residual phase of the first stimulation pulse and not based on a value of a characteristic of an ECAP corresponding to the first stimulation pulse, the value of the parameter that at least partially defines the second stimulation pulse.

25. The medical device of claim **1**, wherein the processing circuitry is configured to:

determine that the plurality of stimulation pulses elicit greater than the threshold ratio of detectable ECAPs to stimulation pulses; and

responsive to the determination, control electrical stimulation therapy based on one or more characteristics of detectable ECAP signals.

26. The medical device of claim **1**, wherein the processing circuitry is configured to:

determine that the plurality of stimulation pulses elicit less than the threshold ratio of detectable ECAPs to stimulation pulses; and

responsive to the determination, control electrical stimulation therapy based on one or more characteristics of detected stimulation pulses.

27. The method of claim **14**, wherein determining whether the plurality of stimulation pulses elicit greater than the threshold ratio of detectable ECAPs to stimulation pulses comprises:

determining that the plurality of stimulation pulses elicit greater than the threshold ratio of detectable ECAPs to stimulation pulses;

responsive to determining that the plurality of stimulation pulses elicit greater than the threshold ratio, control electrical stimulation therapy based on one or more characteristics of detectable ECAP signals;

determining that the plurality of stimulation pulses elicit less than the threshold ratio of detectable ECAPs to stimulation pulses; and

responsive to determining that the plurality of stimulation pulses elicit less than the threshold ratio, control electrical stimulation therapy based on one or more characteristics of detected stimulation pulses.

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