US010881311B2

(12) **United States Patent**
Boettcher et al.

(10) **Patent No.: US 10,881,311 B2**
(45) **Date of Patent: Jan. 5, 2021**

(54) **APPARATUS AND METHOD FOR THE AUTOMATED MEASUREMENT OF SURAL NERVE CONDUCTION VELOCITY AND AMPLITUDE**

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(72) Inventors: **Bonniejean Boettcher**, Maynard, MA (US); **Marc Cryan**, Maynard, MA (US); **Shai N. Gozani**, Brookline, MA (US); **Glenn Herb**, Weston, MA (US); **Xuan Kong**, Acton, MA (US); **Michael Williams**, Melrose, MA (US); **Charles Fendrock**, Sudbury, MA (US)

(73) Assignee: **NeuroMetrix, Inc.**, Waltham, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1196 days.

(21) Appl. No.: **14/931,177**

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(65) **Prior Publication Data**

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Related U.S. Application Data

(63) Continuation of application No. 13/235,258, filed on Sep. 16, 2011, now Pat. No. 9,173,581.
(Continued)

(51) **Int. Cl.**
A61B 5/04 (2006.01)
A61B 5/05 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***A61B 5/04001*** (2013.01); ***A61B 5/05*** (2013.01); ***A61B 5/4041*** (2013.01); *A61B 5/01* (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC A61B 5/04001; A61B 5/4041; A61B 2560/028; A61B 2560/0266;
(Continued)

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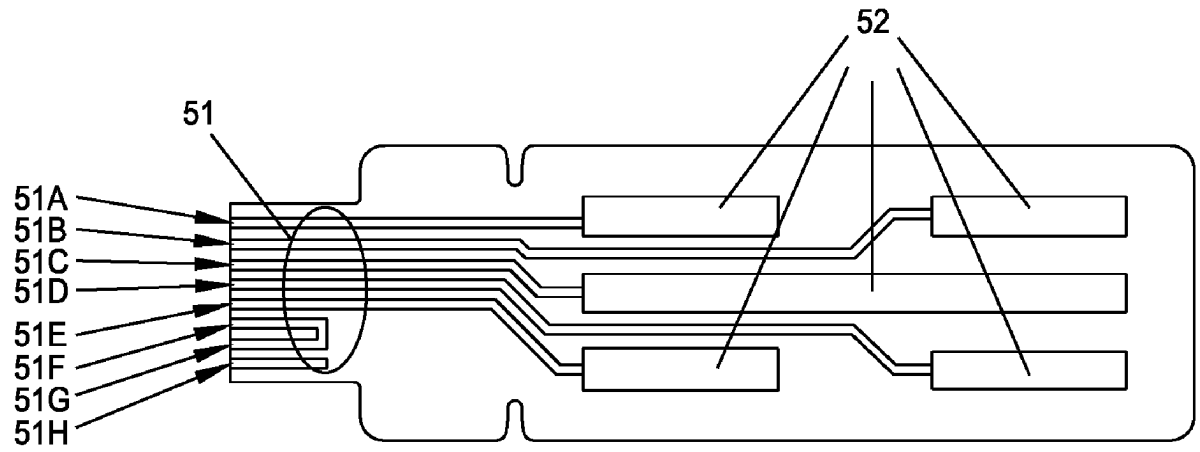
Assistant Examiner — Erin M Cardinal
(74) *Attorney, Agent, or Firm* — Pandiscio & Pandiscio

(57) **ABSTRACT**

Apparatus for measuring sural nerve conduction velocity and amplitude, the apparatus including a housing; stimulation means for electrically stimulating a human sural nerve; a biosensor comprising a plurality of electrodes for detecting a sural nerve response evoked by the stimulation means; acquisition means electrically connected to the biosensor for electrically acquiring the sural nerve response detected by the biosensor; processing means electrically connected to the acquisition means for digitizing, processing and storing the acquired sural nerve response; calculation means electrically connected to the processing means for calculating the conduction velocity and amplitude of the processed sural nerve response; and display means for displaying the sural
(Continued)



nerve conduction velocity and amplitude; wherein the stimulation means and the biosensor are designed to be placed on a patient's anatomy, in the vicinity of a sural nerve.

9 Claims, 15 Drawing Sheets

Related U.S. Application Data

(60) Provisional application No. 61/403,453, filed on Sep. 16, 2010, provisional application No. 61/459,127, filed on Dec. 6, 2010, provisional application No. 61/467,857, filed on Mar. 25, 2011, provisional application No. 61/516,944, filed on Apr. 11, 2011, provisional application No. 61/571,203, filed on Jun. 22, 2011.

(51) **Int. Cl.**
A61B 5/00 (2006.01)
A61B 5/01 (2006.01)

(52) **U.S. Cl.**
CPC . *A61B 2560/028* (2013.01); *A61B 2560/0266* (2013.01); *A61B 2560/0425* (2013.01); *A61B 2560/0468* (2013.01); *A61B 2562/0215* (2017.08); *A61B 2562/046* (2013.01)

(58) **Field of Classification Search**
CPC A61B 1/00062; A61B 5/150885; A61B 2018/00988; A61B 2090/0803; A61B 2090/0814; A61B 2560/0285
See application file for complete search history.

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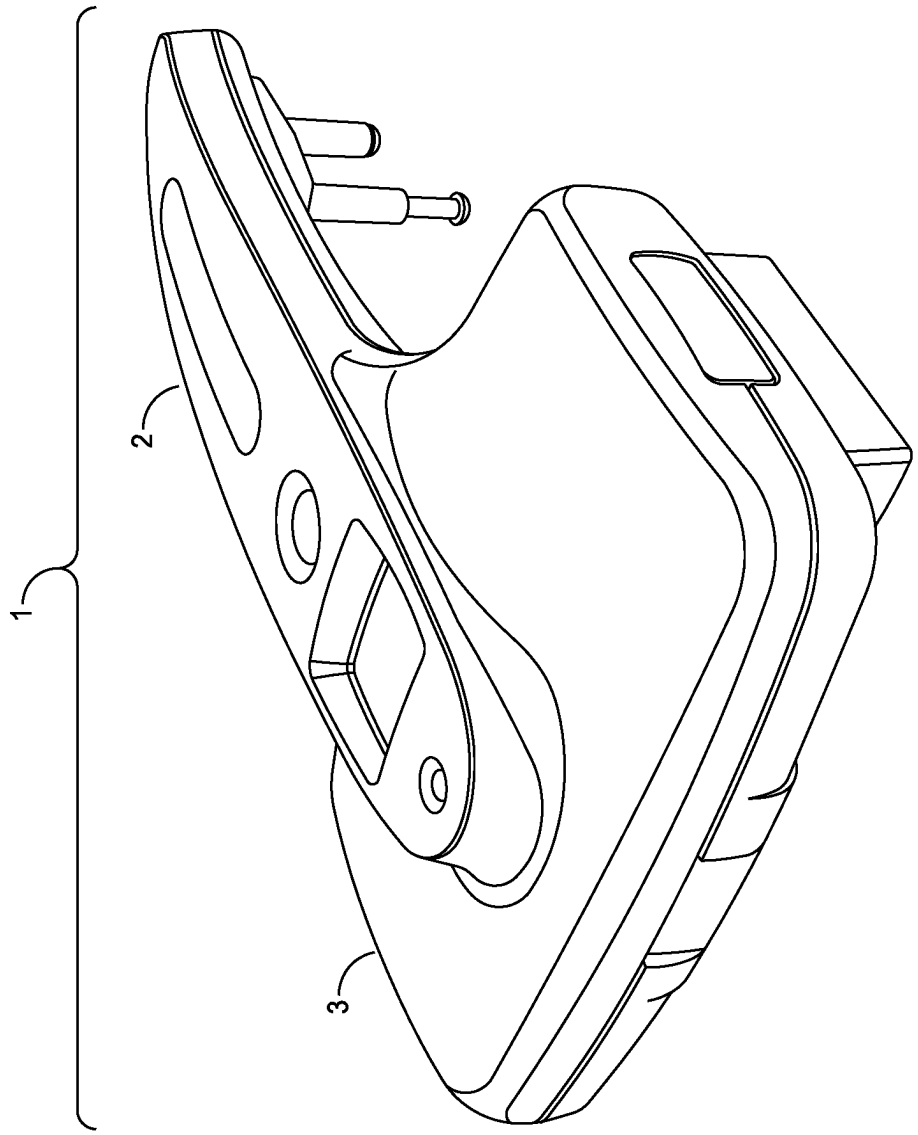

FIG. 1

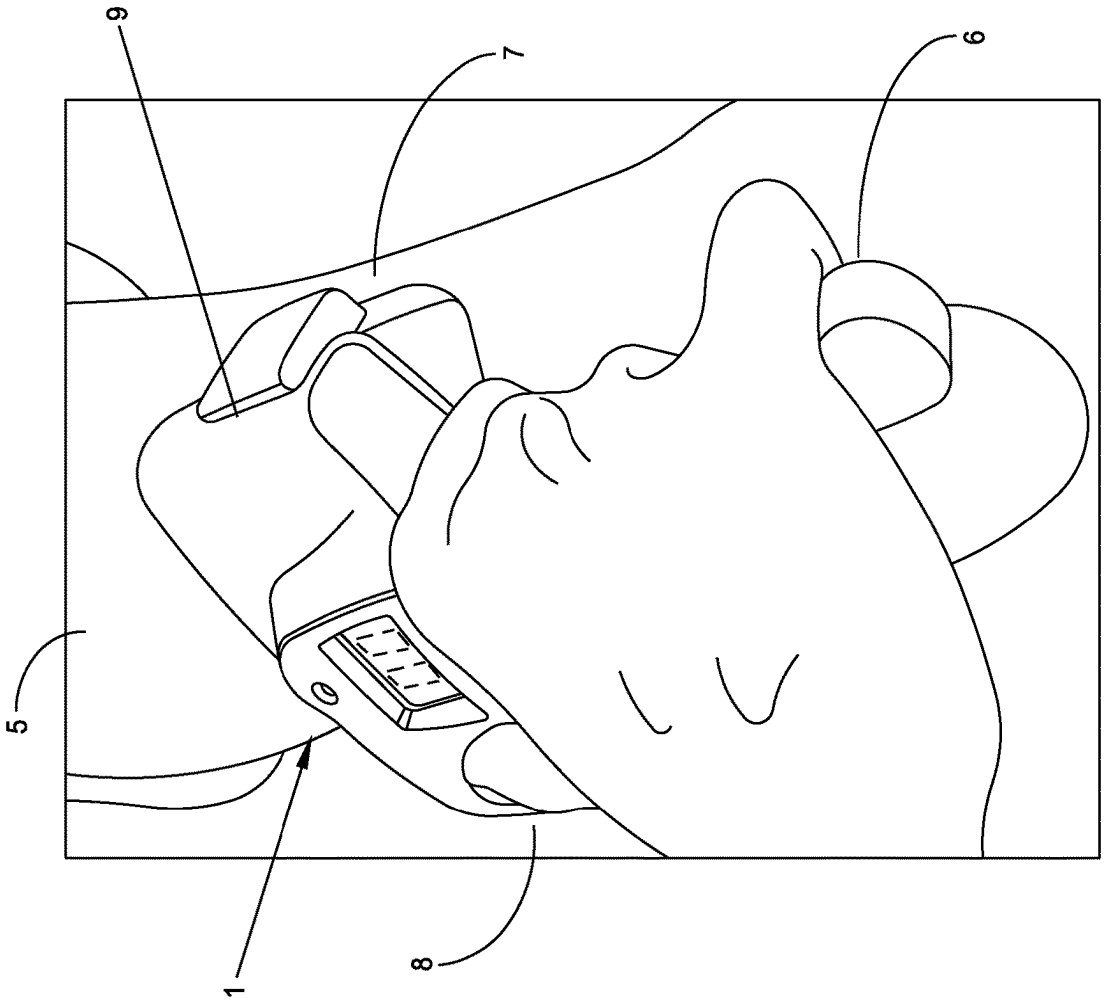

FIG. 2

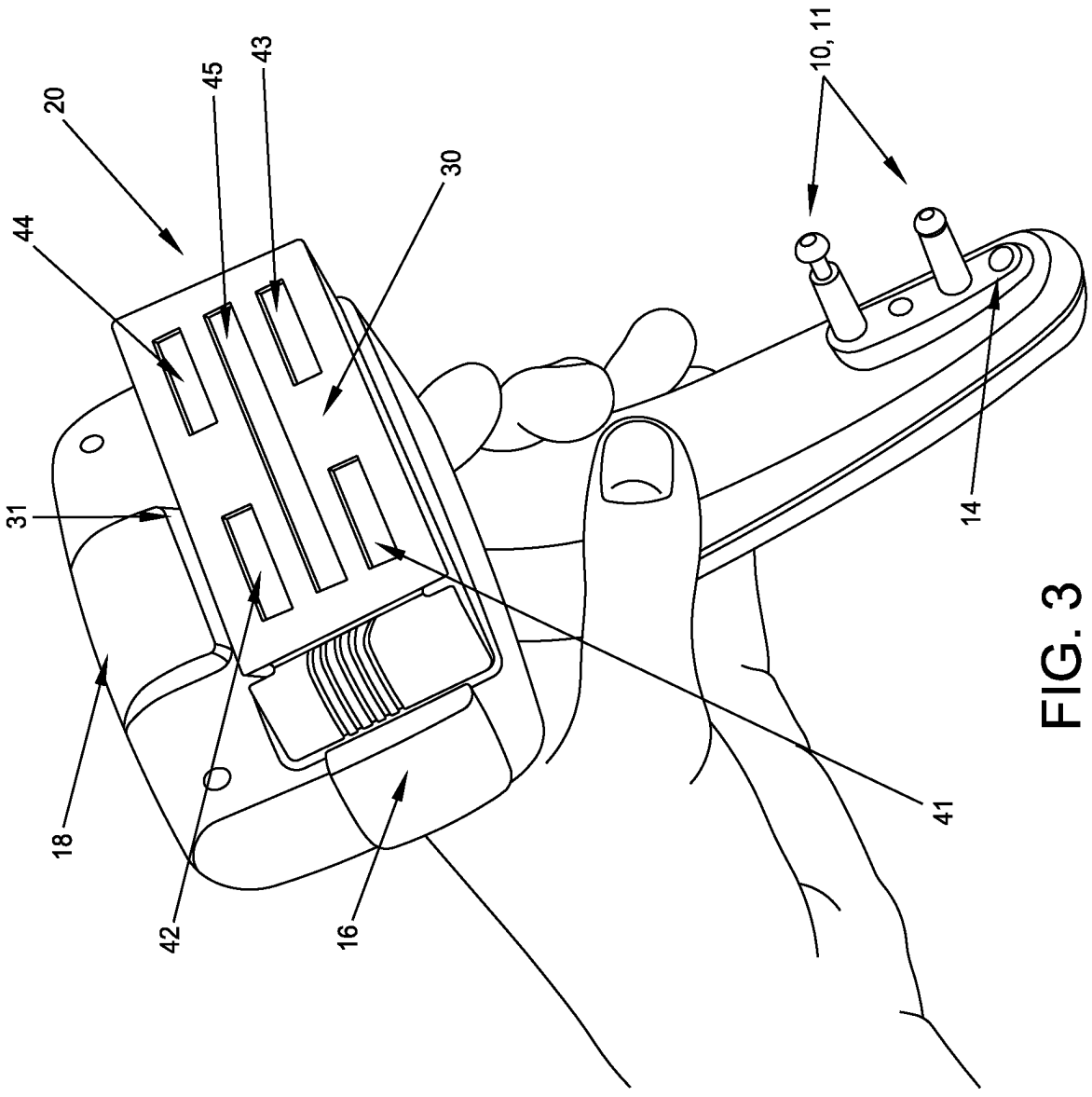

FIG. 3

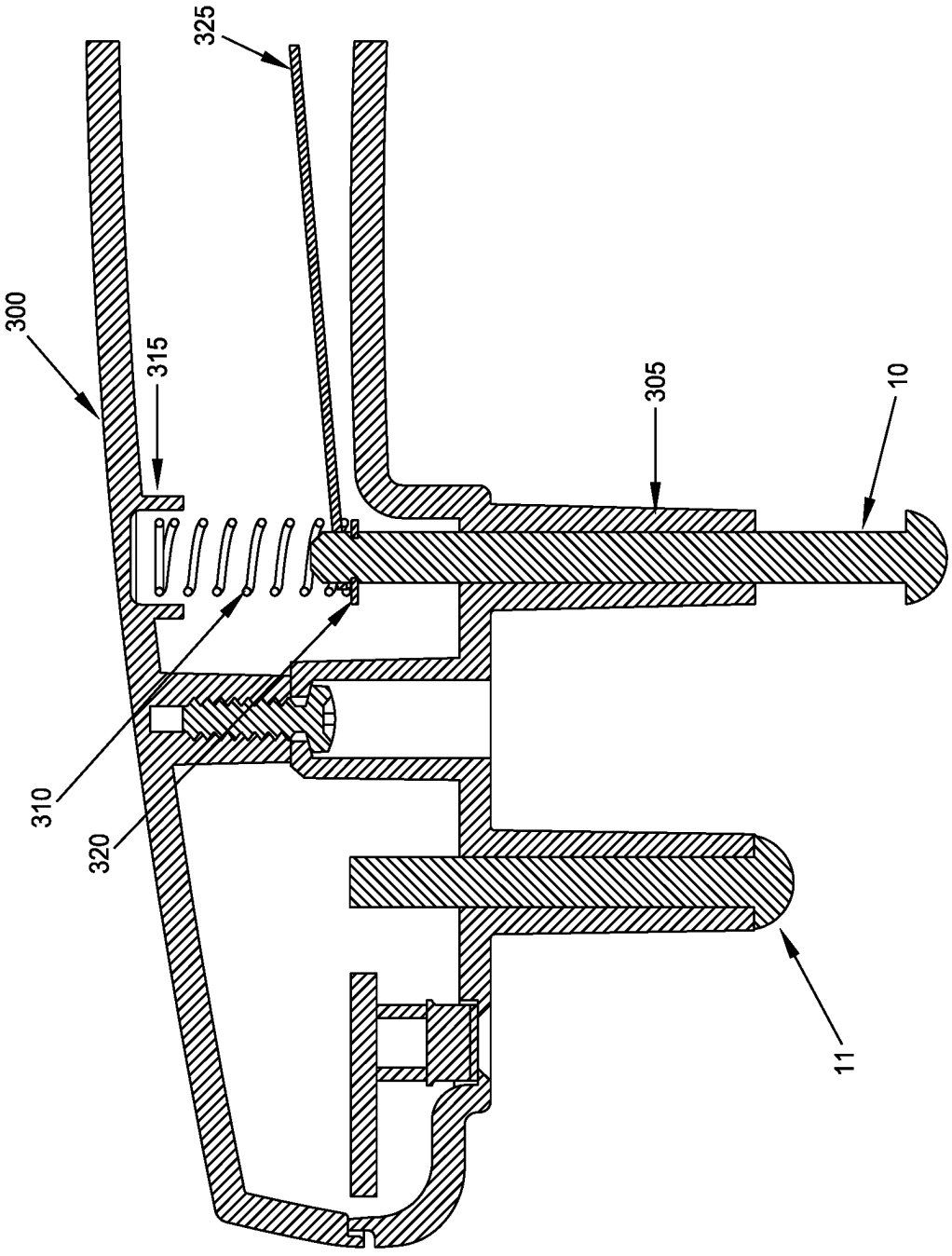

FIG. 3A

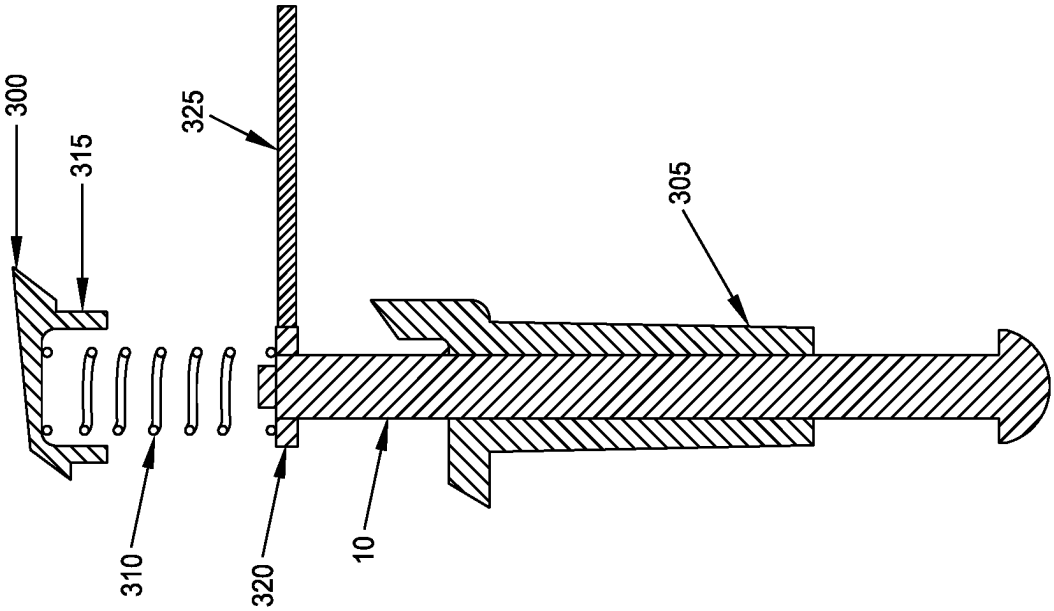

FIG. 3B

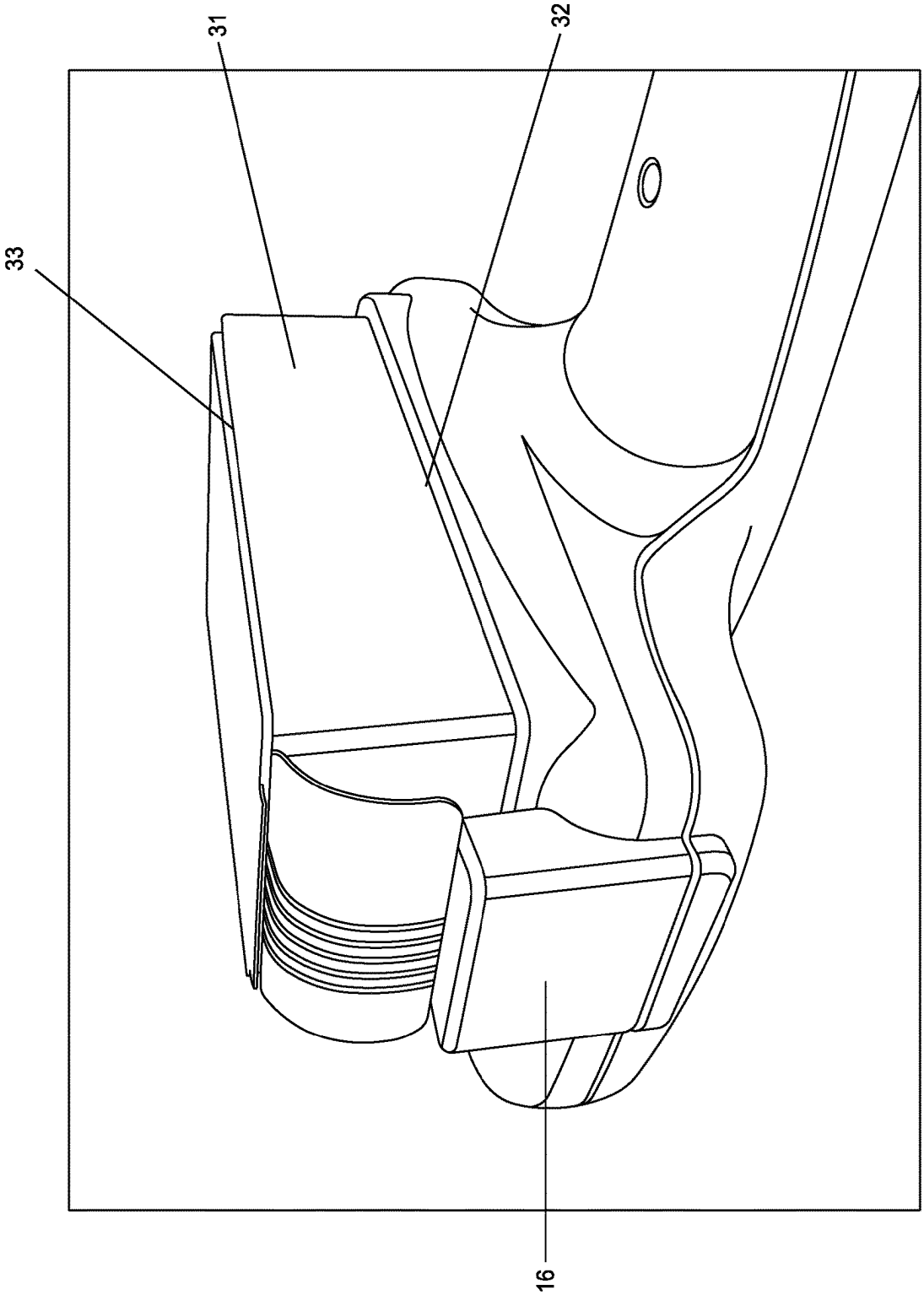

FIG. 4

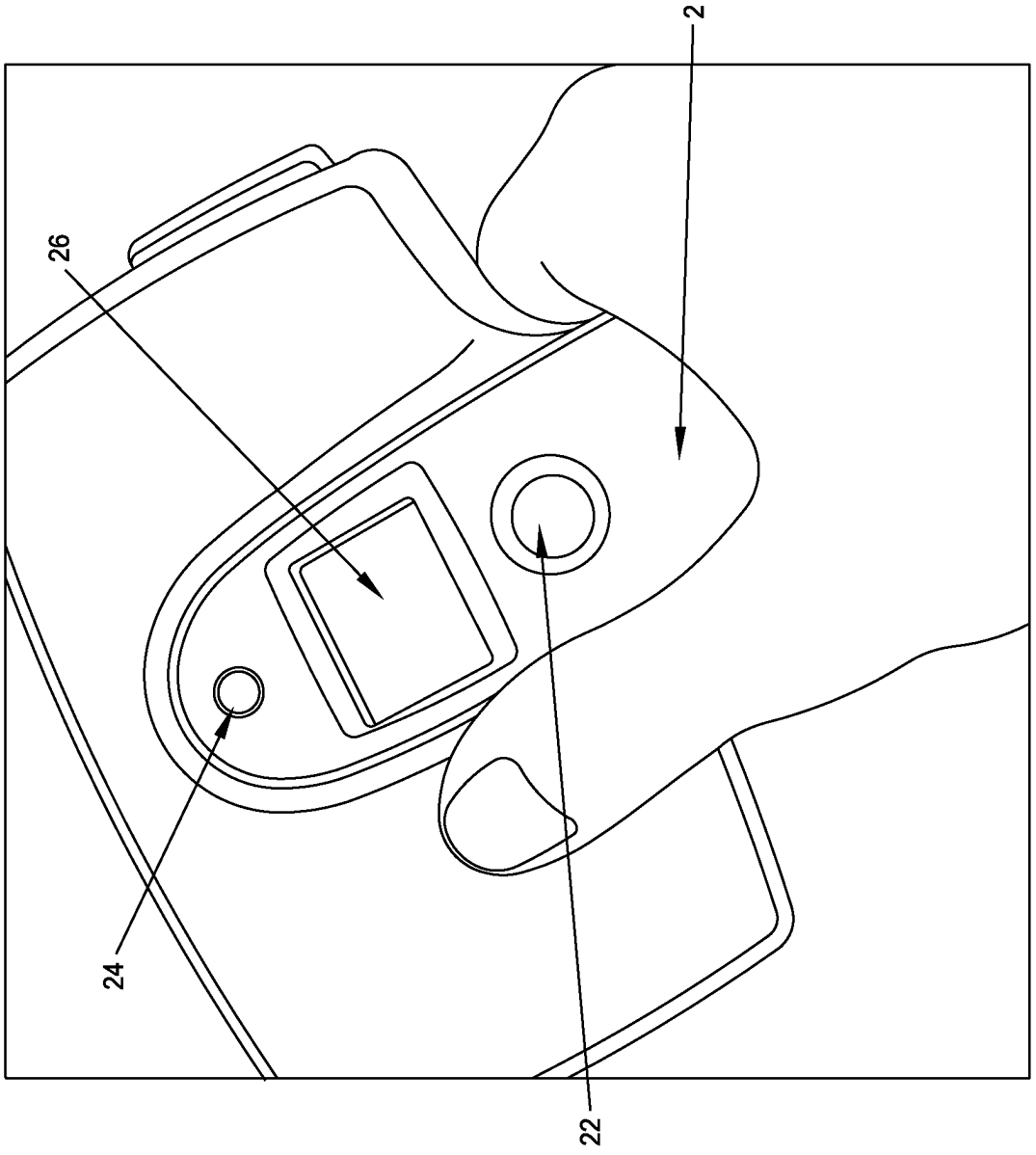

FIG. 5

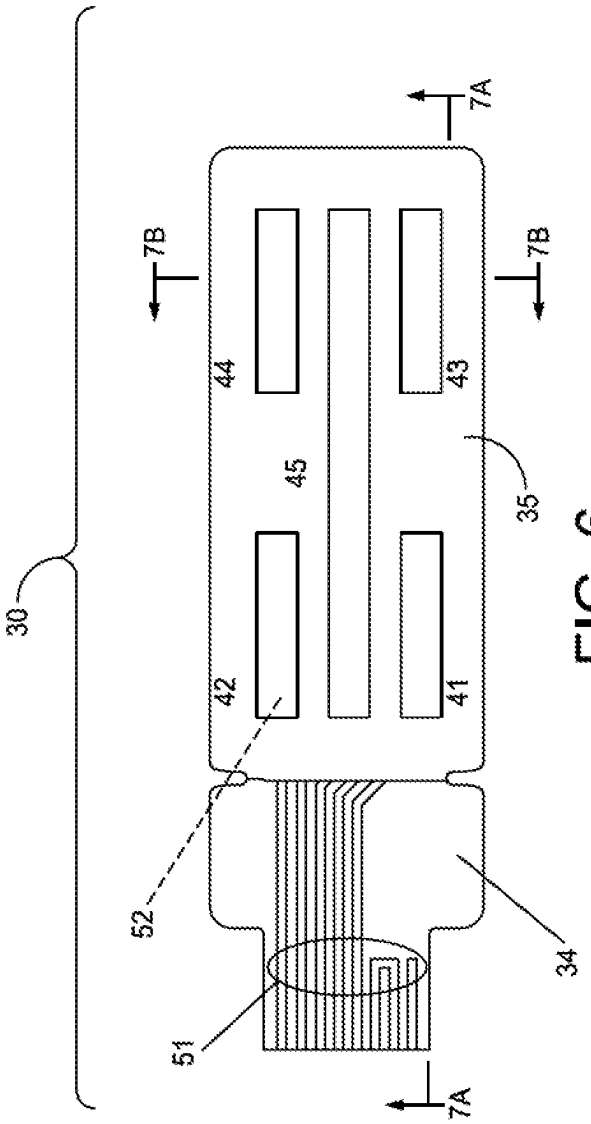

FIG. 6

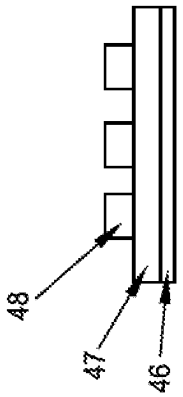

FIG. 6B

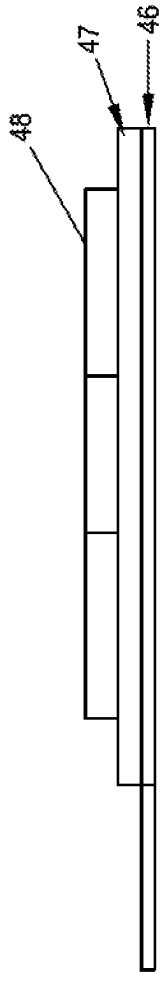

FIG. 6A

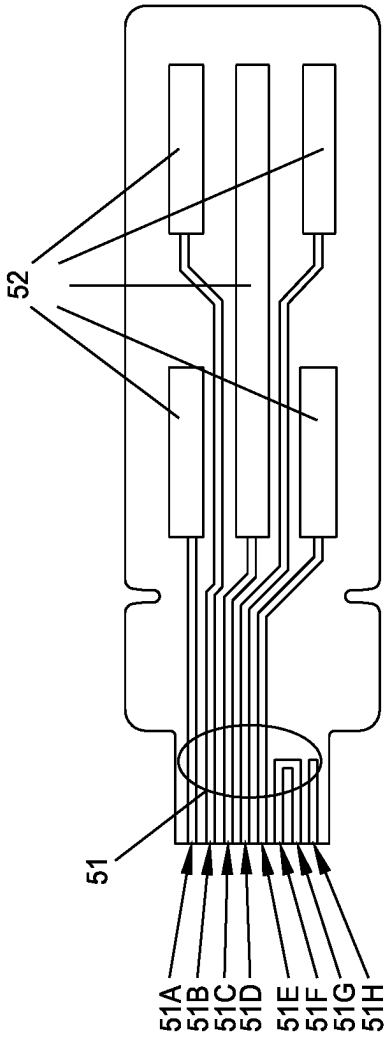

FIG. 7

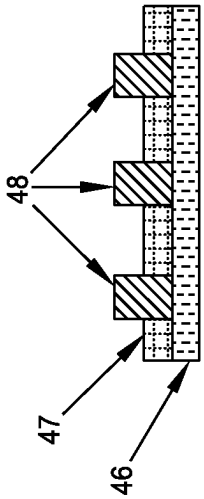

FIG. 7B

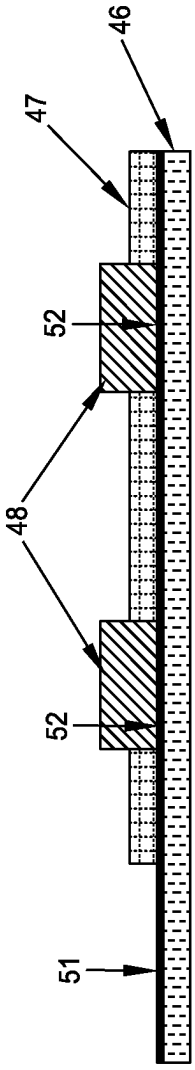

FIG. 7A

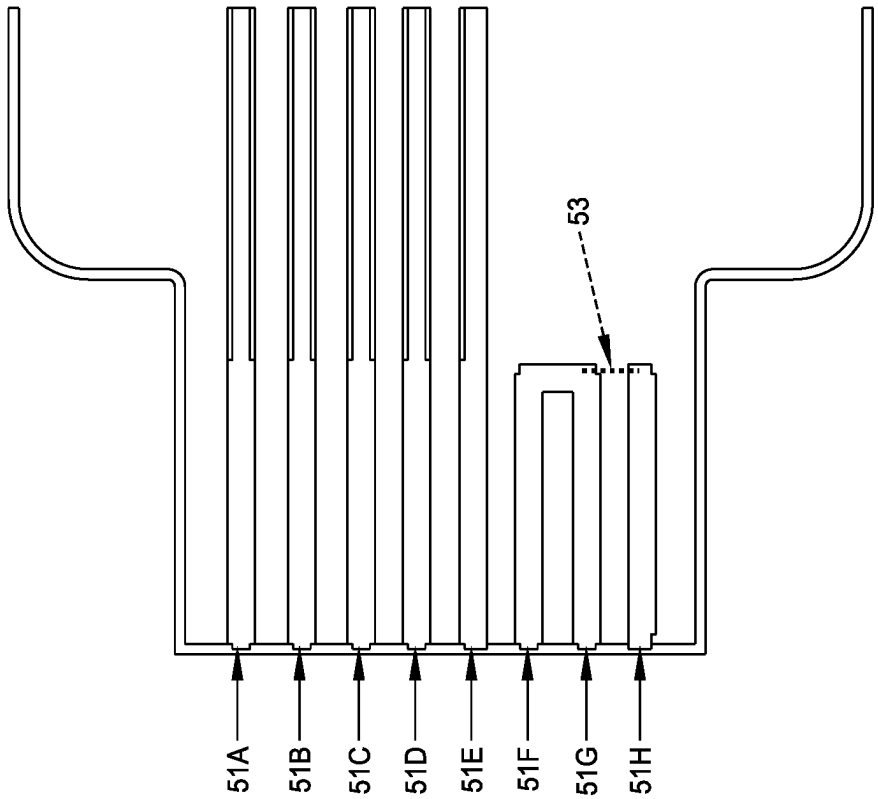

FIG. 7C

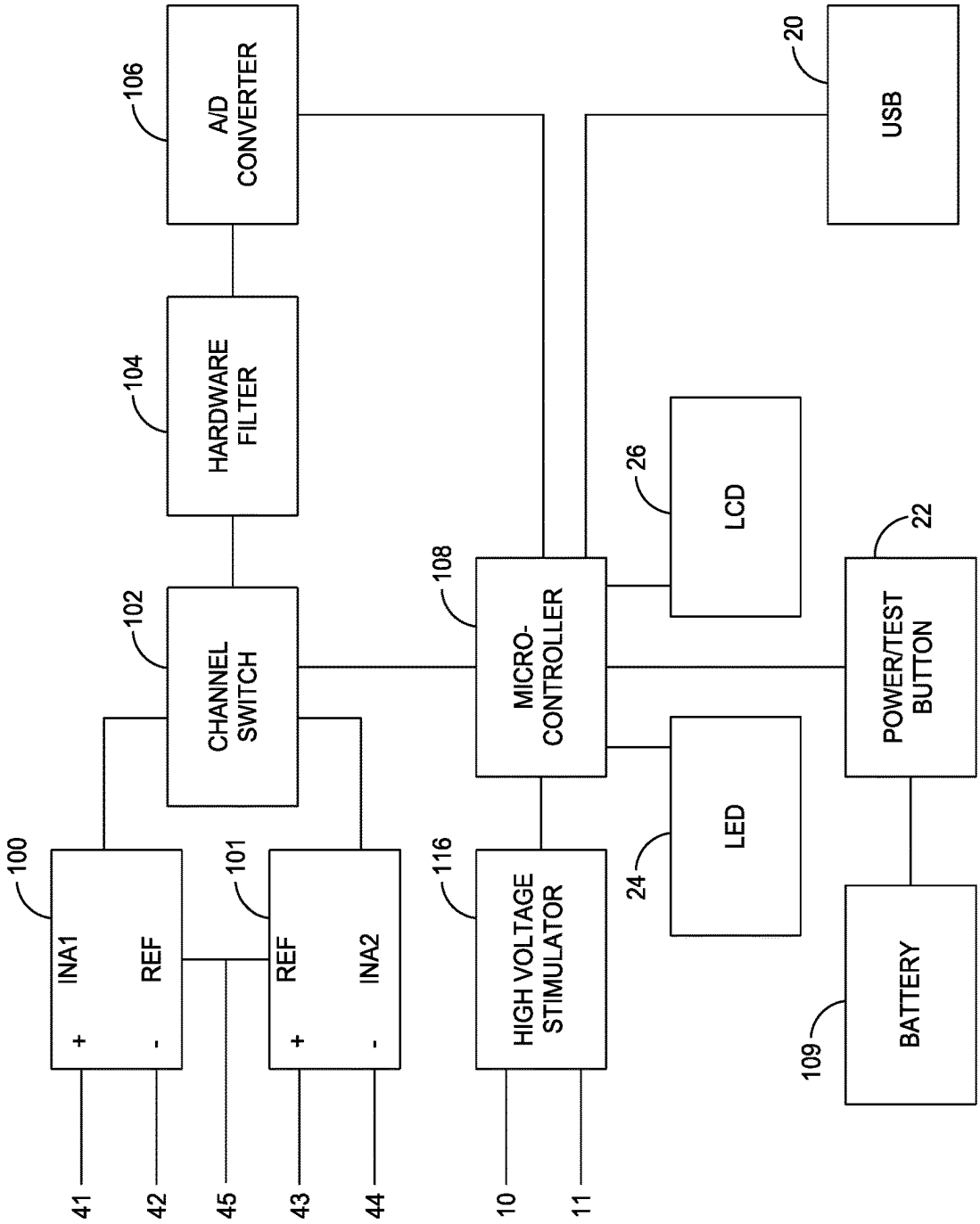
106
A/D CONVERTER
20
USB
104
HARDWARE FILTER
26
LCD
102
CHANNEL SWITCH
108
MICRO-CONTROLLER
22
POWER/TEST BUTTON
LED
24
100
INA1
+
-
REF
101
REF
+
-
INA2
116
HIGH VOLTAGE STIMULATOR
109
BATTERY
41
42
45
43
44
10
11

FIG. 8

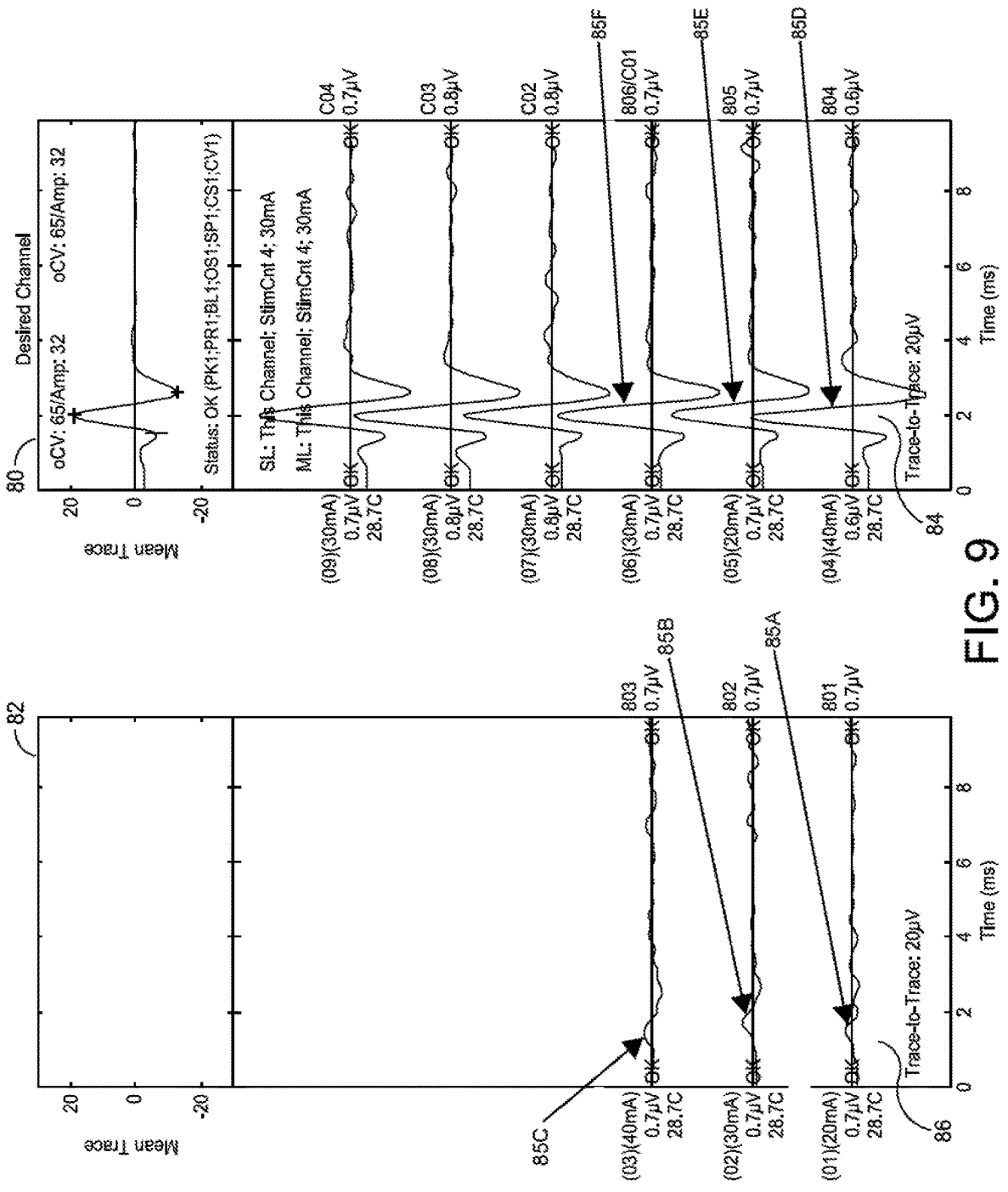
80
Desired Channel
oCV: 65/Amp: 32
oCV: 65/Amp: 32
Status: OK (PK1;PR1;BL1;OS1;SP1;CS1;CV1)
SL: This Channel; StimCnt 4; 30mA
ML: This Channel; StimCnt 4; 30mA
Mean Trace
20
0
-20
C04 0.7µV
C03 0.8µV
C02 0.8µV
806/C01 0.7µV
805 0.7µV
804 0.6µV
85F
85E
85D
(09)(30mA) 0.7µV 28.7C
(08)(30mA) 0.8µV 28.7C
(07)(30mA) 0.8µV 28.7C
(06)(30mA) 0.7µV 28.7C
(05)(20mA) 0.7µV 28.7C
(04)(40mA) 0.6µV 28.7C
Trace-to-Trace: 20µV
84
0
2
4
6
8
Time (ms)
82
803 0.7µV
802 0.7µV
801 0.7µV
85B
85A
85C
(03)(40mA) 0.7µV 28.7C
(02)(30mA) 0.7µV 28.7C
(01)(20mA) 0.7µV 28.7C
Trace-to-Trace: 20µV
86

FIG. 9

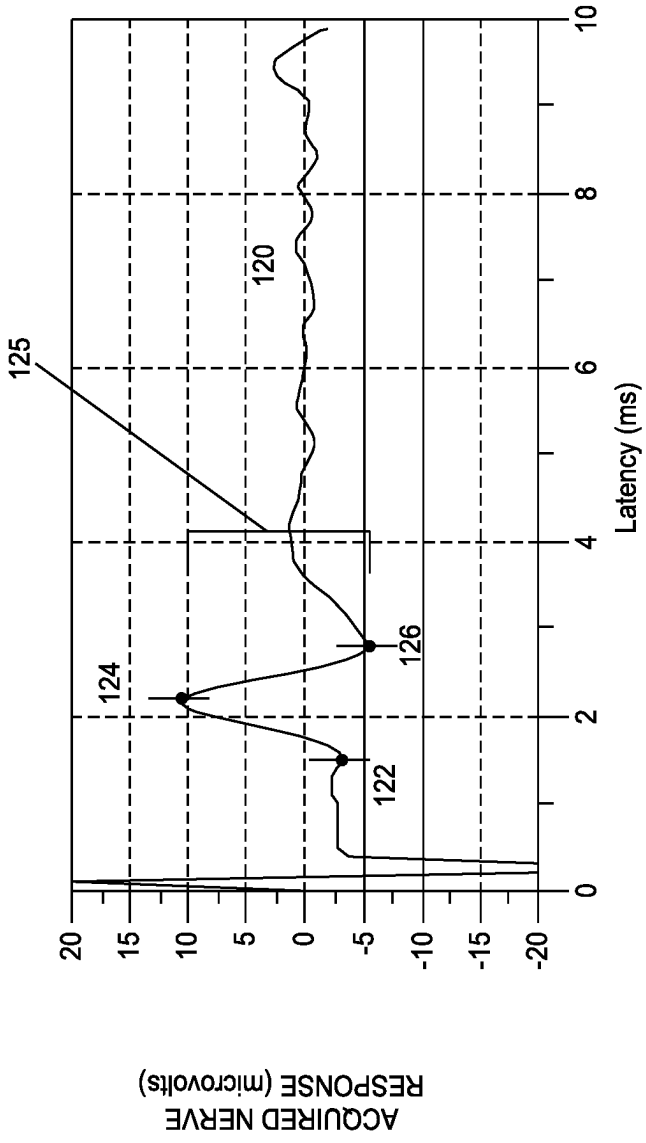
125
120
124
126
122
Latency (ms)
0
2
4
6
8
10
20
15
10
5
0
-5
-10
-15
-20
ACQUIRED NERVE
RESPONSE (microvolts)

FIG. 10

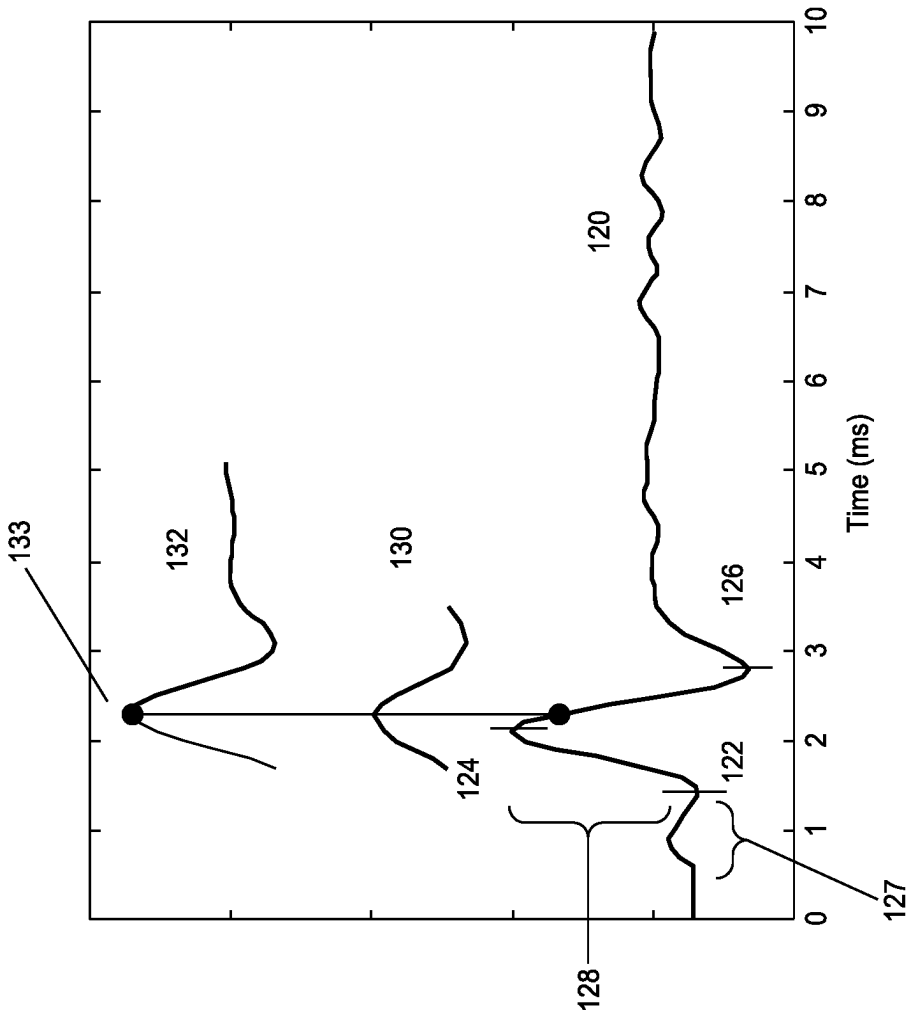

FIG. 11

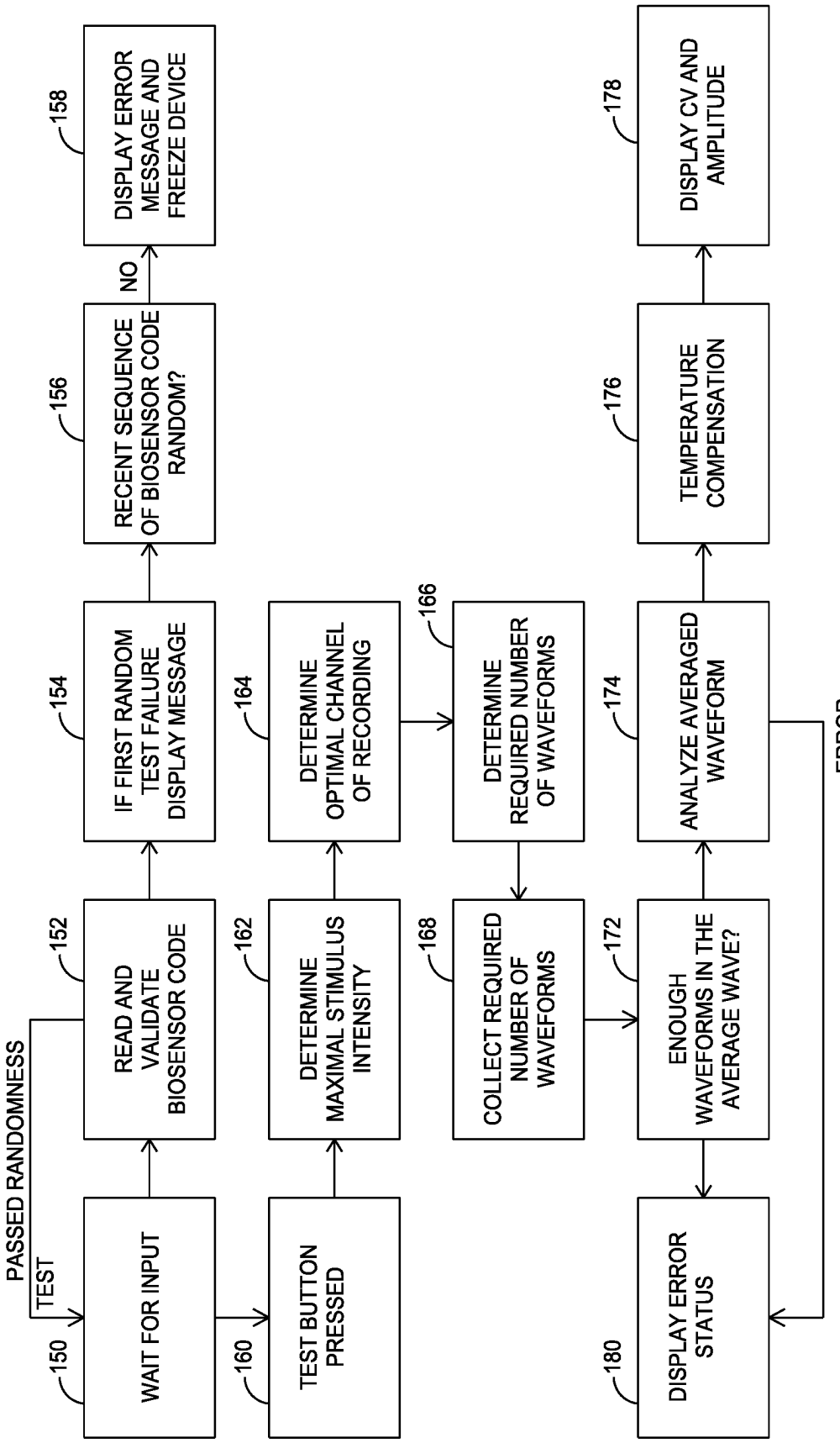
150
WAIT FOR INPUT
PASSED RANDOMNESS
TEST
152
READ AND VALIDATE BIOSENSOR CODE
154
IF FIRST RANDOM TEST FAILURE DISPLAY MESSAGE
156
RECENT SEQUENCE OF BIOSENSOR CODE RANDOM?
NO
158
DISPLAY ERROR MESSAGE AND FREEZE DEVICE
160
TEST BUTTON PRESSED
162
DETERMINE MAXIMAL STIMULUS INTENSITY
164
DETERMINE OPTIMAL CHANNEL OF RECORDING
166
DETERMINE REQUIRED NUMBER OF WAVEFORMS
168
COLLECT REQUIRED NUMBER OF WAVEFORMS
172
ENOUGH WAVEFORMS IN THE AVERAGE WAVE?
174
ANALYZE AVERAGED WAVEFORM
176
TEMPERATURE COMPENSATION
178
DISPLAY CV AND AMPLITUDE
ERROR
180
DISPLAY ERROR STATUS

FIG. 12

APPARATUS AND METHOD FOR THE AUTOMATED MEASUREMENT OF SURAL NERVE CONDUCTION VELOCITY AND AMPLITUDE

REFERENCE TO PENDING PRIOR PATENT APPLICATIONS

This patent application is a continuation of prior U.S. patent application Ser. No. 13/235,258, filed Sep. 16, 2011, now U.S. Pat. No. 9,173,581 issued Nov. 3, 2015, by Bonniejean Boettcher et al. for APPARATUS AND METHOD FOR THE AUTOMATED MEASUREMENT OF SURAL NERVE CONDUCTION VELOCITY AND AMPLITUDE, which patent application claims benefit of:

(i) prior U.S. Provisional Patent Application Ser. No. 61/403,453, filed Sep. 16, 2010 by Shai N. Gozani for NC-STAT® SL;

(ii) prior U.S. Provisional Patent Application Ser. No. 61/459,127, filed Dec. 6, 2010 by Shai N. Gozani for NC-STAT® SL;

(iii) prior U.S. Provisional Patent Application Ser. No. 61/467,857, filed Mar. 25, 2011 by Shai N. Gozani et al. for NC-STAT® SL;

(iv) prior U.S. Provisional Patent Application Ser. No. 61/516,944, filed Apr. 11, 2011 by Bonniejean Boettcher et al. for NC-STAT® SL; and

(v) prior U.S. Provisional Patent Application Ser. No. 61/571,203, filed Jun. 22, 2011 by Shai N. Gozani et al. for NC-STAT® DPNCHECK™.

The above-identified patent applications are hereby incorporated herein by reference.

FIELD OF THE INVENTION

This invention relates to apparatus and methods for the assessment of electrophysiological signals, and more particularly to the assessment of sural nerve conduction velocity and amplitude.

BACKGROUND OF THE INVENTION

Diabetes Mellitus ("DM") is a common disease involving ineffective regulation of blood glucose levels. There are over 25 million people in the United States with DM, and recent projections suggest that over 350 million people have the disease worldwide. There are two primary forms of DM. Type I DM generally affects children and young adults and is related to a primary deficiency of the insulin hormone. Type II DM usually affects adults, often over the age of 50, but increasingly in younger adults as well. It is a complex disease that generally starts as a resistance to insulin action that may progress to secondary insulin deficiency. The causes of Type I and Type II DM are not entirely known although genetic, environmental, and lifestyle risk factors have been identified.

Although acutely high or low blood glucose levels are dangerous, the primary sources of DM-associated morbidity and mortality are the long term macrovascular and microvascular complications of the disease. Macrovascular complications refer to cardiovascular events such as myocardial infarction ("heart attack") and stroke. Microvascular complications refer to pathological damage to the nerves, eyes, and kidneys of people with DM.

The most common microvascular complication of DM is neuropathy, or nerve damage. Diabetic neuropathy affects 60% or more of people with DM. Diabetic neuropathy may include damage to the large myelinated nerve fibers, the small myelinated and unmyelinated nerve fibers, and the autonomic nerves. The most common form of diabetic neuropathy is the large fiber form of the disease which is often termed diabetic peripheral neuropathy ("DPN"). DPN leads to pain and disability, and is the primary trigger for foot ulcers which may result in lower extremity amputations.

Because of the severe consequences of DPN, early detection of this complication of DM, and interventions to prevent or slow down progression of the neuropathy, are of paramount importance. Unfortunately, detection of DPN is challenging, particularly at its early stages when it may be most susceptible to intervention. Current methods of detecting and monitoring DPN range from clinical evaluation (including symptoms and signs obtained on simple physical examination) to various tests that include the 5.07/10-g monofilament test (where a column of "fishing line" is pressed into the foot of the patient, with the goal being for the patient to detect the contact before the column of "fishing line" bends), the tuning fork test (where a vibrating tuning fork is placed against the big toe of the patient, with the goal being for the patient to detect the vibration of the tuning fork), and quantitative vibration perception testing (where electronics are used to measure the magnitude of a vibration detectable by the patient). While all of these methods have utility, they are subjective, have inadequate sensitivity or specificity, or both, and have poor reproducibility. The "gold standard" method for evaluation of DPN is a nerve conduction study. In a nerve conduction study, a nerve is electrically stimulated at a first location along the nerve, and then the electrical response of the nerve is detected at a second location along the nerve. Among other things, the rate at which the nerve conducts the signal ("the nerve conduction velocity") and the magnitude of the evoked signal ("the amplitude") are reliable indicators of neuropathy. Unlike the aforementioned techniques, nerve conduction testing is objective, sensitive, specific, and reproducible. As a result, most clinical guidelines suggest confirmation of DPN by nerve conduction testing for a reliable diagnosis.

Despite its technical and clinical attributes, nerve conduction testing is not currently widely used in the detection and monitoring of DPN. The reasons for this include the limited availability, complexity and high cost of the study when performed by specialists, usually a neurologist, using traditional electrodiagnostic equipment. To overcome these obstacles to adoption, a number of devices have been developed to simplify and increase access to nerve conduction studies through automation and other techniques. For example, devices that perform nerve conduction measurements using pre-fabricated, nerve-specific electrode arrays have been developed that largely automate the required technical steps of a nerve conduction study (see, for example, U.S. Pat. No. 5,851,191 issued to Gozani et al. and U.S. Pat. No. 7,917,201 issued to Gozani et al.). Another related solution found in the prior art (see U.S. Pat. No. 5,215,100 issued to Spitz et al.) is an apparatus for the assessment of Carpal Tunnel Syndrome (CTS) in which all the electrodes required to stimulate and record from the nerve are fixed by the device.

These prior art solutions suffer from a number of deficiencies. All devices described in the prior art are either general purpose (i.e., multi-nerve, multi-application) nerve conduction testing devices or they are designed specifically for evaluation of the median nerve for the assessment of CTS. General purpose devices, of necessity, must adapt to the various anatomical and electrophysiological aspects of

many different nerves. As a result, only limited customization is possible and the onus remains on the user of the general purpose device to address the sources of variations—such as through the placement of individual electrodes or even pre-configured electrode arrays. As a result, despite simplifying nerve conduction measurements relative to the traditional approaches, the general purpose testing devices still require a fair amount of training in order to properly perform the nerve conduction test procedures. Also, those devices in the prior art specifically designed for the evaluation of the median nerve have little relevance to the requirements of the present invention, which is the assessment of the sural nerve. The primary reason for this is that the anatomy and electrophysiology of the sural nerve (used for the assessment of DPN) is substantially different from that of the median nerve (used for the assessment of CTS). Therefore devices specifically designed for testing of the median nerve cannot be used to test the sural nerve. Another issue with general purpose testing devices is that they require two discrete components—a device with the electronic circuits needed to perform a nerve conduction test, and a nerve-specific electrode array which provides an interface between the unique characteristics of the particular nerve being tested and the common testing device. This two-component requirement limits attempts to reduce test costs, particularly because it restricts the ability to reduce the size of the electrode array, which is a primary cost driver in nerve conduction testing.

SUMMARY OF THE INVENTION

The present invention is a fully-integrated, hand-held sural nerve conduction testing device. The sural nerve is a sensory-only nerve located in the lower calf and ankle region of the body. Sural nerve conduction is a standard and quantitative biomarker of DPN. Sural nerve conduction testing detects DPN with high diagnostic sensitivity and reveals abnormalities before there is clinical evidence of neuropathy. Sural nerve conduction is correlated to the morphological severity of myelinated fiber loss and is therefore predictive of foot ulcer risk.

The purpose of this new device is to easily, rapidly, and accurately measure and report two common sural nerve conduction parameters: the onset conduction velocity (hereafter abbreviated as "CV") and the sensory response amplitude (hereafter described as "amplitude"). The term "fully-integrated" indicates that all of the components needed for performing a nerve conduction test of the sural nerve are incorporated into a single physical unit, as opposed two or more distinct components (for example, an electrode array and a testing instrument connected by a cable). The term "hand-held" indicates that the device is applied to the patient by a qualified user in order to test the nerve, rather than being a fixed apparatus into which the patient places their limb. The "fully-integrated" and "hand-held" characteristics require technological advances that are both novel and non-obvious.

The present invention addresses the deficiencies of the prior art. First, the current device is designed and optimized for testing of the sural nerve. As a result, the test procedure has been substantially simplified and automated to the point where it can be taught to someone in 30-60 minutes after which they should be able to obtain accurate sural nerve conduction results. Further, due to its focused application on the sural nerve, the test procedure has been automated to the point where the test duration is typically only 15-30 seconds in length. Another benefit of its focused application on the sural nerve is that the cost of both the hardware and disposable components have been substantially reduced relative to the general purpose devices described in the prior art.

In one preferred form of the present invention, there is provided apparatus for measuring sural nerve conduction velocity and amplitude, the apparatus comprising:

a housing;

stimulation means mounted to the housing for electrically stimulating a human sural nerve;

a biosensor releasably mounted to the housing, the biosensor comprising a plurality of electrodes for detecting a sural nerve response evoked by the stimulation means;

acquisition means mounted to the housing and electrically connected to the biosensor for electrically acquiring the sural nerve response detected by the biosensor;

processing means mounted to the housing and electrically connected to the acquisition means for digitizing, processing and storing the acquired sural nerve response;

calculation means mounted to the housing and electrically connected to the processing means for calculating the conduction velocity and amplitude of the processed sural nerve response; and

display means mounted to the housing for displaying the sural nerve conduction velocity and amplitude;

wherein the stimulation means and the biosensor are designed to be placed on a patient's anatomy, in the vicinity of a sural nerve, by manipulating the housing.

In another preferred form of the present invention, there is provided apparatus for measuring sural nerve conduction velocity and amplitude, the apparatus comprising:

a housing;

stimulation means mounted to the housing for electrically stimulating a human sural nerve;

a seat on the housing for releasably mounting a biosensor to the housing, wherein the biosensor is of the type comprising a plurality of electrodes for detecting a sural nerve response evoked by the stimulation means;

acquisition means mounted to the housing for electrical connection to a biosensor mounted on the seat and for electrically acquiring the sural nerve response detected by the biosensor;

processing means mounted to the housing and electrically connected to the acquisition means for digitizing, processing and storing the acquired sural nerve response;

calculation means mounted to the housing and electrically connected to the processing means for calculating the conduction velocity and amplitude of the processed sural nerve response; and

display means mounted to the housing for displaying the sural nerve conduction velocity and amplitude;

wherein the stimulation means and a biosensor releasably mounted on the seat are designed to be placed on a patient's anatomy, in the vicinity of a sural nerve, by manipulating the housing.

In another preferred form of the present invention, there is provided apparatus for measuring sural nerve conduction velocity and amplitude, the apparatus comprising:

a biosensor adapted to be releasably mounted to the housing of a nerve conduction testing device so that the biosensor moves in conjunction with the housing, the biosensor comprising a plurality of electrodes for detecting a sural nerve response evoked by the nerve conduction testing device and an electrical connector for electrically connecting the plurality of electrodes to the nerve conduction testing device.

In another preferred form of the present invention, there is provided a method for measuring sural nerve conduction velocity and amplitude, the method comprising:

releasably mounting a biosensor to the housing of a nerve conduction testing device so that the biosensor moves in conjunction with the housing;

positioning the housing of the nerve conduction testing device so that the nerve conduction testing device is positioned to electrically stimulate a human sural nerve and the biosensor is positioned to detect a sural nerve response evoked by the stimulation means;

using the nerve conduction testing device to electrically stimulate a sural nerve and to acquire the sural nerve response detected by the biosensor; and

processing the acquired sural nerve response to determine the conduction velocity and amplitude of the processed sural nerve response.

In another preferred form of the present invention, there is provided a fully-integrated, hand-held nerve conduction testing apparatus comprising a hand-held component and a single-patient use biosensor, wherein the biosensor is both physically and electrically connected to the hand-held component to acquire a nerve response.

In another preferred form of the present invention, there is provided a biosensor for detecting a nerve response, the biosensor comprising:

a substrate;

a plurality of electrodes mounted to the substrate for detecting the nerve response; and

a biosensor reuse code carried by the substrate for determining reuse of the biosensor, wherein the biosensor reuse code is randomly assigned to that biosensor.

In another preferred form of the present invention, there is provided a kit comprising:

a plurality of biosensors for detecting nerve responses, wherein each of the biosensors comprises a substrate, a plurality of electrodes mounted to the substrate for detecting a nerve response, and a biosensor reuse code carried by the substrate for determining reuse of the biosensor;

wherein the biosensor reuse code varies randomly among the biosensors in the kit.

In another preferred form of the present invention, there is provided a method for determining the reuse of a biosensor in connection with a test machine, the method comprising the steps of:

connecting a biosensor to the test machine, wherein the biosensor comprises a biosensor reuse code randomly assigned to that biosensor;

identifying the biosensor reuse code associated with the connected biosensor;

comparing the identified biosensor reuse code with the biosensor reuse codes associated with the biosensors previously connected to the test machine; and

determining that the biosensor has been reused if the comparison indicates that the identified biosensor reuse code and the codes from the previously connected biosensors form a pattern that is unlikely from a random distribution of biosensor reuse codes, or determining that the biosensor has not been reused if the aforementioned pattern is likely from a random distribution of biosensor reuse codes.

In another preferred form of the present invention, there is provided a method for preventing the reuse of a biosensor in connection with a test machine, the method comprising the steps of:

connecting a biosensor to the test machine, wherein the biosensor comprises a biosensor reuse code randomly assigned to that biosensor;

identifying the biosensor reuse code associated with the connected biosensor;

comparing the identified biosensor reuse code with the biosensor reuse codes associated with the biosensors previously connected to the test machine; and

allowing the test to proceed if the comparison indicates that the identified biosensor reuse code is part of a random distribution of biosensor reuse codes, or preventing the test from proceeding if the comparison indicates that the identified biosensor reuse code is not part of a random distribution of biosensor reuse codes.

In another preferred form of the present invention, there is provided an adapter for connecting a biosensor to a testing device, the adapter comprising a biosensor reuse code carried by the adapter for determining reuse of the biosensor, wherein the biosensor reuse code is presented by the adapter to the testing device.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other objects and features of the present invention will be more fully disclosed or rendered obvious by the following detailed description of the preferred embodiments of the invention, which is to be considered together with the accompanying drawings wherein like numbers refer to like parts, and further wherein:

FIG. **1** is a schematic view of a novel, fully-integrated, hand-held sural nerve conduction testing device formed in accordance with the present invention;

FIG. **2** is a schematic view showing the testing device of FIG. **1** being placed on a patient's limb;

FIG. **3** is a schematic view of the bottom of the testing device shown in FIG. **1**;

FIGS. **3**A and **3**B are schematic sectional views showing the preferred construction details for the spring-loaded cathode of the testing device shown in FIG. **1**;

FIG. **4** is a schematic view showing selected portions of the testing device of FIG. **1**, including the biosensor, foam pad, and device head;

FIG. **5** is a schematic view of the top of the testing device shown in FIG. **1**;

FIG. **6** is a schematic view of the top of the biosensor;

FIG. **6**A is a schematic side view of the biosensor shown in FIG. **6**;

FIG. **6**B is a schematic end view of the biosensor shown in FIG. **6**;

FIG. **7** is another schematic view of the top of the biosensor shown in FIG. **6**;

FIG. **7**A is a schematic cross-sectional view taken along line **7**A-**7**A of FIG. **6**;

FIG. **7**B is a schematic cross-sectional view taken along line **7**B-**7**B of FIG. **6**;

FIG. **7**C is an enlarged schematic view of selected portions of the traces of the biosensor shown in FIG. **6**;

FIG. **8** is a high level hardware schematic of the testing device shown in FIG. **1**;

FIG. **9** is a schematic view showing sural nerve responses from two recording channels;

FIG. **10** is an example of an algorithmic analysis of a sural nerve response;

FIG. **11** is an example of how to determine sural nerve response waveform features; and

FIG. **12** is a high level functional schematic of the preferred control algorithm for the testing device of FIG. **1**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Device Description

The present invention is a fully-integrated, hand-held sural nerve conduction testing device. The device is designed exclusively for non-invasive nerve conduction measurements of the human sural nerve in the region of the lower calf and ankle. The sural nerve is an almost-entirely sensory nerve formed from the merger of the medial and lateral sural cutaneous nerves which are branches of the tibial and common fibular nerves (which are themselves branches of the sciatic nerve). After forming at the distal third of the gastroc muscle, the sural nerve runs down the leg on the posterior-lateral side, then posterior to the lateral malleolus where it runs deep to the fibularis tendon sheath and reaches the lateral tuberosity of the fifth toe, where it ramifies. The sural nerve transmits sensory signals from the posterior lateral corner of the leg, the lateral foot and the 5th toe.

Sural nerve conduction is a standard and quantitative biomarker of DPN. Sural nerve conduction testing detects DPN with high diagnostic sensitivity and reveals abnormalities before there is clinical evidence of neuropathy. Sural nerve conduction is correlated to the morphological severity of myelinated fiber loss and is therefore predictive of foot ulcer risk.

There are a variety of nerve conduction methodologies by which the sural nerve can be evaluated. For example, the nerve can be tested orthodromically by stimulating the nerve at the ankle and then measuring the nerve response after it has conducted a known distance up the calf, or the nerve can be tested antidromically by stimulating the nerve in the calf and then measuring the nerve response after it has conducted a known distance to the ankle. Another methodological factor in nerve conduction testing for the sural nerve includes the distance between the points of stimulation and recording, which generally varies from about 8 cm to 16 cm. Another methodological factor associated with nerve conduction testing of the sural nerve is the configuration of the recording electrodes, including their shape, size, and the distance between them. In the preferred embodiment of the present invention, the sural nerve is tested orthodromically with a stimulation-to-recording distance of 9.22 cm. The preferred recording electrode configuration is provided below in the description of the biosensor.

The purpose of the present invention is to easily, rapidly, and accurately measure and report two common sural nerve conduction parameters: the onset conduction velocity (hereafter abbreviated as "CV") and the sensory response amplitude (hereafter described as "amplitude"). The term "fully-integrated" indicates that all of the components needed for performing a nerve conduction test of the sural nerve are incorporated into a single physical unit, as opposed two or more distinct components (for example, an electrode array and a testing instrument connected by a cable). The term "hand-held" indicates that the device is applied to the patient by a qualified user in order to test the nerve, rather than being a fixed apparatus into which the patient places their limb. The "fully-integrated" and "hand-held" characteristics require technological advances that are both novel and non-obvious.

An overall view of the present invention is provided in FIG. **1**. As shown, the invention comprises a single fully-integrated, hand-held device **1** with a narrow handle **2** and a head **3**. In the preferred embodiment, device **1** is 19.0 cm in length and 11.5 cm in width at its widest point on head **3**. The most critical dimension is the distance between cathode **10** (FIG. **3**) of device **1** (which is the point of nerve stimulation) and the center of the electrodes **41**, **43** on the biosensor **30**. When biosensor **30** is seated in the biosensor port **16** (FIG. **3**), electrodes **41**, **43** are closest to cathode **10**. That distance (i.e., the distance between cathode **10** and electrodes **41**, **43**) represents the conduction distance between the point of nerve stimulation via cathode **10** and arrival of the evoked nerve impulse at electrodes **41**, **43**. This distance is 9.22 cm in the preferred construction and is used to calculate the CV as will be described below.

A preferred use of the invention is shown in FIG. **2**. As shown, device **1** is placed against the lateral aspect of the patient's lower leg **5** such that (i) the stimulation probes **10**, **11** (FIG. **3**) mechanically contact the leg immediately behind the outside ankle bone ("lateral malleoulus") **6**, and (ii) biosensor **30** contacts the patient's lower calf **7**, with the inner edge (one of the two sides **8** or **9**, depending on the limb) of device **1** being approximately aligned with the Achilles tendon. In order to reliably measure nerve conduction of the sural nerve, device **1** must have enough degrees of freedom in order to conform to the patient's lower leg anatomy and thereby allow for robust and stable contact of certain device components (i.e., the stimulating electrodes and the detecting electrodes) with the patient. The means to accomplish this robust electrical contact are described in detail below.

FIG. **3** is a bottom view of the preferred embodiment of device **1**. This view shows the surfaces that contact the patient. There are two stainless steel probes **10**, **11** for electrically stimulating the sural nerve when device **1** is placed against the patient in the manner shown in FIG. **2**. The cathode **10** has a variable height relative to handle **2** due to its spring-loaded construction. In the preferred embodiment this variable height ranges from 2.5 cm (compressed condition) to 3.3 cm (uncompressed condition) from handle **2**. The anode **11** preferably has a fixed height relative to handle **2**, which in the preferred embodiment is fixed at 2.3 cm from the handle. The variable length cathode **10** is novel inasmuch as it provides a degree of freedom to enable robust contact of both stimulating probes **10**, **11** with the patient anatomy in the vicinity of the ankle, which is non-planar and has a topology which varies from patient to patient. Although it is possible to electrically stimulate the sural nerve through the stimulating probes **10**, **11** by direct contact with the patient's skin, it is preferable to use a small amount of conductive hydrogel on the outer tip of each probe so as to reduce the impedance of the probe-skin interface.

FIGS. **3**A and **3**B show one preferred construction for the spring-loaded cathode **10**. More particularly, in this form of the invention, device **1** comprises a plastic enclosure **300** which forms the body of device **1**, with plastic enclosure **300** comprising a tubular projection **305** for slidably receiving cathode **10** therein. A spring **310** is captured between the proximal end of cathode **10** and a seat **315** formed on plastic enclosure **300**. A fastener **320** may be used to secure spring **310** to the proximal end of cathode **10** if desired. A flexible cable **325** electrically connects cathode **10** to the stimulation source. Also shown in FIGS. **3**A and **3**B is the fixed anode **11**.

Device **1** includes an infra-red thermometer **14** (FIG. **3**) for non-contact measurement of the patient's skin surface temperature in the vicinity of the ankle bone. As will be discussed below, this temperature measurement is used to compensate for the effects of temperature on nerve conduction results. The use of a non-contact temperature measuring

device is an important aspect of the present invention, since it permits reliable temperature measurements to be made in the irregular skin surface topology associated with the sural nerve.

Head **3** of device **1** supports biosensor **30**, which provides a bioelectrical interface to the patient. Biosensor **30**, which is described in detail below, is disposable and should be replaced between patients. Biosensor **30** is secured to device **1** by a foam pad **31** (FIGS. **3** and **4**) which is provided with non-permanent adhesive on both sides of the foam pad—the adhesive on the inner surface of foam pad **31** releasably secures the foam pad to head **3** of device **1**, and the adhesive on the outer surface of foam pad **31** releasably secures biosensor **30** to the foam pad. Foam pad **31** is disposable but may be used for multiple patients as it does not come in direct contact with the patient. Foam pad **31** is shown in greater detail in FIG. **4**. One side **32** of the foam pad attaches to the bottom surface of head **3** of device **1**, and the other side **33** attaches to the non-patient contact side of biosensor **30**. In the preferred embodiment, foam pad **31** is 2.2 cm thick. Although various types of foam may be used, in the preferred embodiment, polyurethane foam is used. When device **1** is pressed against the patient's leg as shown in FIG. **2**, the foam pad provides multiple degrees of freedom by which biosensor **30** may conform to the patient's anatomy so as to establish complete contact with the patient's skin. A uniform and complete contact between electrodes **41**, **42**, **43**, **44** and **45** (FIG. **3**) and patient skin makes it possible to acquire high quality nerve conduction signals over a wide variety of patient anatomy. The use of foam pad **31** in achieving a uniform and complete contact of electrodes and patient skin is novel and non-obvious. Biosensor **30** is connected to the internal electronics of device **1** via biosensor port **16**.

Thus it will be seen that device **1** includes (i) novel means for ensuring reliable electrical contact between the stimulating electrodes and the skin of the patient (i.e., the spring-loaded cathode **10** and the fixed-position anode **11**), and (ii) novel means for ensuring reliable electrical contact between the detecting electrodes and the skin of the patient (i.e., the use of foam pad **31** to support biosensor **30**).

Head **3** of device **1** includes a battery compartment **18** (FIG. **3**) with a removable door for replacement of the battery **109** (FIG. **8**), which in the preferred embodiment is a widely available 3V Lithium Ion battery (CR123A). A mini USB port **20** (FIG. **3**) allows for device **1** to communicate with external devices (such as a PC) using the standard USB protocol.

FIG. **5** shows the top of device **1**, which provides the user interface. In the preferred embodiment, the user interface consists of one push-button switch **22**, an LED **24**, and an LCD **26**. Push-button switch **22** turns on device **1** if the device is powered off. If device **1** is powered on, then switch **22** initiates a nerve conduction test. LED **24** has three colors (green, amber, and red) and is used to indicate device status, which may include green to represent "ready to test," amber to indicate "battery low," and red to indicate "error—cannot perform test." In the preferred embodiment, LCD **26** is a two 7-segment display with additional dot indicators. LCD **26** displays the results of the sural nerve conduction test or an error status **180** (see FIG. **12**) to the user. A successful test is accompanied by a toggling display on the LCD of (i) the numerical values of the CV, and (ii) the amplitude of the nerve response (or an amplitude of 0, without a CV, to indicate that sural nerve conduction is not detectable). An unsuccessful test is accompanied by an error status message **180** (see FIG. **12**) on LCD **26** which indicates the probable cause for the failure. In the preferred embodiment, the error status messages include "Sn" for an error related to the biosensor, "Er" for an error related to excessive muscle interference, "Pr" for an error related to stimulating probes, and "° C." for an error related to patient skin surface temperature.

Biosensor Description

A preferred embodiment of biosensor **30** is shown in FIGS. **6**, **6**A, **6**B, **7**, **7**A and **7**B. Biosensor **30** is a multi-layer construct of mylar **46**, Ag (silver) traces **51**, Ag—AgCl pads **52**, foam **47**, and hydrogels **48**. Biosensor **30** also comprises a patient contact area **35** and a device connection tail **34** (FIG. **6**). Patient contact area **35** preferably has a width 8.77 cm and a height 3.77 cm. Tail **34** electrically connects biosensor **30** to device **1** via biosensor port **16**. Biosensor **30** consists of 5 discrete electrodes **41**, **42**, **43**, **44**, **45** that are comprised of hydrogel layered on top of an Ag—AgCl pad. The four smaller electrodes (**41**, **42**, **43** and **44**) are electrically connected to the differential inputs of instrumentation amplifiers (see below) and therefore function as "active" electrodes. The single long electrode **45** is connected to the reference input of the instrumentation amplifiers and therefore functions as a "reference" electrode. In the preferred embodiment of biosensor **30**, the electrodes are connected so as to form two distinct sural nerve response recording channels. In particular, electrodes **41** and **42** comprise one recording channel, and electrodes **43** and **44** comprise a second distinct recording channel. Alternative embodiments of the present invention include biosensors comprised of only one recording channel, or biosensors comprised of three or more recording channels. Alternative configurations of reference electrode **45** include multiple distinct reference electrodes rather than a single common reference electrode.

In the preferred embodiment shown in FIG. **6**, the active recording electrodes **41**, **42**, **43** and **44** each have dimensions of 2.5 cm by 0.5 cm, and the reference electrode **45** has dimensions 0.5 cm by 7.0 cm. The two active electrodes comprising each recording channel (i.e., **41**, **42** and **43**, **44**) are preferably separated by a distance of 2.0 cm measured center to center. The reference electrode **45** is preferably separated by 1.0 cm from each of the active electrodes **41**, **42**, **43**, **44** measured center to center.

Tail **34** of biosensor **30** provides an electrical connection between device **1** and biosensor **30** via biosensor port **16**. Tail **34** is the male connector, and biosensor port **16** is the female connector. In the preferred form of the invention, tail **34** comprises 8 parallel traces **51**. Five of the traces (**51**A, **51**B, **51**C, **51**D and **51**E) connect electrodes **41**, **42**, **43**, **44**, **45**, respectively, to the corresponding inputs on the aforementioned instrumentation amplifiers. Two of the traces (**51**F and **51**G) are connected together such that when tail **34** of biosensor **30** is inserted into biosensor port **16** of device **1**, an electrical circuit is closed. This closed circuit allows device **1** to detect and thereby confirm that biosensor **30** is connected to device **1**. Confirmation is indicated to the user by a steady green color on LED **24**. One trace (**51**H) represents a 1-bit biosensor code which is used by the device software to determine whether biosensors **30** are being reused on multiple patients. The bit is coded as 0 or 1, depending on whether that trace (**51**H) is connected (e.g., via a connector **53**, see FIG. **7**C) to one of the other traces (**51**F, **51**G), which is connected to ground upon insertion of tail **34** into device **1**. It is intended that the 1-bit biosensor code associated with a given biosensor be randomly distributed, i.e., one-half of all biosensors **30** are intended to have a "0"

1-bit biosensor code, and one-half of all biosensors **30** are intended to have a "1" 1-bit biosensor code. The manner in which this 1-bit biosensor code is used to detect biosensor reuse is discussed below in the software description.

Hardware Description

FIG. **8** is a block diagram of a preferred embodiment of the internal electronics (hardware) of device **1**. The hardware consists of two instrumentation amplifiers (INA) **100**, **101** with differential inputs coming from the two pairs of active electrodes **41**, **42** and **43**, **44**. In the preferred embodiment, these INAs have a typical input impedance $\geq 10^{10}$ (10 to the 10^{th} power) Ohms and a common mode rejection ratio ≥90 dB. The INAs **100**, **101** share a common reference input coming from reference electrode **45**. The outputs of INAs **100**, **101** are fed into a 2×1 switch **102** that determines which of the two channels will be acquired and processed. Switch **102** is controlled by the microcontroller **108**, with the channel selection determined by the test control software (see below). The channel selection may be different at different stages of the testing. The output of switch **102** is input into a band-pass filter **104**. In the preferred embodiment, band-pass filter **104** has a low frequency cutoff of 2 Hz and a high frequency cutoff of 4900 Hz. The output of band-pass filter **104** is then digitized by the A/D converter **106**, with the digital output going into the microcontroller **108** for storage and processing.

Microcontroller **108** triggers the high voltage stimulator **116** to deliver nerve stimulation to the patient via cathode **10** and anode **11**. In a preferred embodiment, the high voltage stimulator **116** is a constant current stimulator that generates a monophasic square DC pulse with a duration of 50 to 100 psecs. The output voltage of the high voltage stimulator is 400-440 V, with a typical value of 420 V. The high voltage stimulator is capable of delivering up to 100 mA into a 3.3 kOhm load.

Microcontroller **108** controls the user interface components including LED **24**, LCD **26**, and power/test button **22**. Microcontroller **108** also communicates with an isolated USB port **20** (FIG. **3**) for external communication (such as with a PC). The internal electronics of device **1** are powered from a single battery **109**. In the preferred embodiment, this is the commonly-available 3V Lithium battery CR123A.

Principles of Operation

A nerve conduction test is performed on the patient by placing device **1** against the patient in the manner shown in FIG. **2** and described above. When in this disposition, cathode **10** is located over the sural nerve as the sural nerve passes behind the lateral malleoulus **6** (FIG. **2**), and biosensor **30** is located over (or in a worst case, adjacent to) the sural nerve as the sural nerve approaches the Achilles tendon, about 9 cm from cathode **10**. An important object of the present invention is that device **1** automatically adapts to testing either the left leg or the right leg of the patient. This "limb independence" is achieved because when device **1** is placed on the patient as described above, one of the two electrode pairs **41**, **42** or **43**, **44** of biosensor **30** will overlie (or lie immediately adjacent to) the patient's sural nerve. The appropriate electrode pair (i.e., **41**, **42** or **43**, **44**) will be the electrode pair which is closest to the Achilles tendon because the sural nerve crosses the tendon about 9-11 cm proximal to the lateral malleolus. In this configuration, the distance from stimulating cathode **10** to the first electrode (**41** or **43**) within each electrode pair (**41**, **42** or **43**, **44**) is 9.22 cm, and this is the distance used to determine the conduction velocity.

FIG. **9** shows an example of sural nerve responses acquired from the two electrode pairs (**41**, **42** and **43**, **44**). The right panel **80** shows the signals **84** recorded from the electrode pair that overlies the nerve, and the left panel **82** shows the signals **86** recorded from the electrode pair that does not overlie the nerve. It will be appreciated that the electrical signals **86** acquired by the "non-intersecting" electrode pair are small compared to the electrical signals acquired by the "intersecting" electrode pair. This is due to the signal-attenuating effects of volume conduction between the sural nerve and the "non-intersecting" electrode pair. By contrast, the signals **84** from the "intersecting" electrode pair are large due to the much smaller distance between the sural nerve and these electrodes.

Thus it will be seen that by providing two parallel electrode pairs **41**, **42** and **43**, **44**, device **1** can automatically adapt to testing either the left leg or the right leg, with the appropriate electrode pair being readily determinable by a comparison of the magnitude of the signals acquired by each electrode pair.

Software

Device **1** is controlled by a software-based control algorithm which resides on microcontroller **108** (or, alternatively, on an associated storage unit). FIG. **12** provides an overview of various functional blocks of the control algorithm. Upon power up, the control algorithm is in state **150** and waits for an external event, which in the preferred embodiment may be any one of the following: biosensor port insertion, USB port insertion, and test button pressed.

Biosensor Port Insertion

This event is triggered by insertion of a biosensor **30** into biosensor port **16** of device **1**. The primary purpose of this software module is to verify that a biosensor is not used across patients. Upon this event trigger, the control algorithm **152** reads the 1-bit biosensor code associated with the inserted biosensor and determines if this code, along with the recent history of earlier biosensor codes, is randomly distributed (which it should be if the biosensor is not being reused, since the biosensors have a randomly distributed 1-bit biosensor code). In the preferred embodiment of the control algorithm, a history of the most recent twenty-four biosensor codes is checked for randomness using the Runs-Test, which is also called the Wald-Wolfowitz test. This test, shown at **154**, determines if the series of 0s and 1s in the 24-bit sequence is random to a certain level of specificity. In the preferred embodiment, the target specificity is set at 99%. If any 24-bit sequence is determined to be not random, then a warning message is displayed on device LCD **26**, and the 24-bit sequence is reset. If a second 24-bit sequence fails the randomness test (function block **156**), then device **1** is locked by function block **158** and no further testing can be performed until device **1** is reset by the manufacturer.

USB Port Insertion

This part of the control algorithm is executed when a USB cable is inserted into USB port **20**. Upon detection of this event, the control algorithm goes into the USB communications module which implements a basic serial communication protocol between device **1** and an external device

(such as a PC). This USB communications module supports several functions including uploading the most recent test data and downloading a software upgrade.

Test Button Pressed

This part of the control algorithm is executed when test button **22** (FIG. **5**) is pressed. Upon detection of this event (function block **160**), the control algorithm goes into the test control module which implements a sural nerve conduction test. A sural nerve conduction test is comprised of several sequential steps as described below.

STEP **1**. Proper measurement of nerve conduction requires that the nerve is stimulated at the "maximal" level. This "maximal" level is defined as the stimulus intensity such that further increasing of the intensity of the stimulus does not increase the nerve response. In the preferred embodiment (function block **162**), this is accomplished by sequentially increasing the stimulus intensity from 20 mA to 60 mA in 10 mA steps. Starting with 30 mA and with each succeeding stimulus intensity, the last two nerve responses are compared with one another. If they are similar in amplitude and shape, as determined by their correlation to one another and to a generic sural nerve response template, then the stimulus intensity is considered to be maximal. In the preferred embodiment, the correlation is implemented as a sum of the products of the two response waveforms (or a response waveform and a generic template), normalized by the square root of the product of the energy in each response waveform (or a response waveform and a generic template). However, if desired, similarity measures different from the correlation technique mentioned above may also be used. If a maximal stimulus intensity is not found, then subsequent data collection is performed at 60 mA.

As described previously, a key object of the present invention is to automatically adapt to measurements from the left or right leg. In order to accomplish this, the sural nerve responses shown in panels **80**, **82** (FIG. **9**) from the two electrode pairs **41**, **42** and **43**, **44** are compared during STEP **1** to determine which of the two pairs overlies the nerve and therefore constitutes the optimal recording channel. In the preferred embodiment (function block **164**), this is achieved by obtained sural responses from both electrode pairs **41**, **42** and **43**, **44** under the same stimulus intensity conditions and comparing selected waveform characteristics—specifically, the responses are compared with respect to their amplitude 125, estimated signal-to-noise ratio, and timing of negative peak **124**. The electrode pair with a larger amplitude, higher signal-to-noise ratio, and earlier negative peak is selected. In the preferred embodiment, the sural response comparison is performed at two stimulus intensity levels: 40 mA and the maximal stimulus intensity level. If the maximal stimulus intensity level is not found, the comparison occurs at 60 mA. Nerve responses from the selected electrode pair (i.e., **41**, **42** or **43**, **44**) are then used in STEP **2** (below) and STEP **3** (below) for determining the sural nerve response amplitude and conduction velocity.

Additionally, the control algorithm of the preferred embodiment also keeps a history of the selected optimal recording channel from previous tests. More particularly, if a device is preferentially used to test one leg more often than the other leg in a given test environment (e.g., due to user preference, a particular test bed setup, etc.), the corresponding pattern can be easily detected from the history of previous tests. The control algorithm can then utilize this information to improve the test efficiency by starting the data acquisition at the preferred recording channel. As an example, and referring now to FIG. **9**, if a test starts at the non-optimal recording channel, waveforms **85**A, **85**B, **85**C will be collected. Since the acquired waveforms will not meet the maximal stimulus intensity criteria, waveform **85**D from the other channel will be acquired at 40 mA stimulus intensity. Comparison of waveforms **85**C and **85**D will lead to subsequent data acquisition from the second recording channel and waveforms **85**E and **85**F will be collected. Waveforms **85**E and **85**F will meet maximal stimulation criteria. Therefore, six waveforms (**85**A, **85**B, **85**C, **85**D, **85**E, and **85**F) are needed to complete STEP **1** as described above where the test starts on the non-optimal recording channel. Alternatively, and as implemented in the preferred embodiment of the invention, if the control algorithm detects a preferential pattern in the previous test history, it starts the test at the preferential recording channel. Then the waveform acquisition sequence will be different. More particularly, it will start by collecting waveforms **85**E and **85**F. Since these two waveforms **85**E (acquired with 20 mA) and **85**F (acquired with 30 mA) will meet the maximal stimulation criteria, the control algorithm will just need to acquire waveform **85**B (stimulated with 30 mA) from the alternative recording channel to allow for a comparison between the two recording channels. Therefore, only three waveforms (**85**E, **85**F, and **85**B) are required in order to complete STEP **1** when the control algorithm utilizes the optimal recording channel history of previous tests and identifies a preferential recording channel.

STEP **2**. Upon determination of the maximal stimulus intensity level, device **1** will repeatedly stimulate the sural nerve at the maximal stimulus intensity level and average the nerve responses into a mean nerve response. In the preferred embodiment (function blocks **166**, **168** and **172**), the number of waveforms averaged is either 4 or 8 depending on the estimated signal-to-noise ratio of the first nerve response obtained at the maximal stimulus intensity level. If the signal-to-noise ratio is low, then 8 responses are averaged, and if the signal-to-noise ratio is high, then 4 responses are averaged. During waveform averaging, device **1** will exclude responses that are "outliers". In the preferred embodiment of the present invention, outliers are determined by comparing a given response to the running average of prior responses.

STEP **3**. FIG. **10** shows an example of an averaged sural nerve response **120** obtained by device **1**. In the preferred embodiment (function block **174**), device **1** determines three key waveform features: the nerve response onset **122**, the response negative peak **124**, and the response positive peak **126**. These nerve response features are determined by a signal processing algorithm. The preferred embodiment of this signal processing algorithm is demonstrated through an example waveform shown in FIG. **11**. Waveform **120** is a result of averaging one or more sural nerve responses. A generic sural nerve response template **130** is also constructed from a collection of waveforms acquired from multiple test subjects under the same data acquisition conditions (such as filter bandwidth and sampling frequency). As template **130** is slid from left-to-right (denoting a shift in time), a correlation between the shifted template **130** and the averaged waveform **120** at different time shifts can be constructed as the correlation **132**. In the preferred embodiment, the correlation is implemented as a sum of the products of the averaged waveform and the shifted template, normalized by the square root of the product of the energy in the averaged waveform **120** and the template **130**. However, other forms of correlations may also be used if desired. The algorithm first determines the time **133** at which maxi-

mum correlation between the averaged response **120** and a fixed generic sural nerve response template **130** is achieved. The local maximum value of the averaged sural nerve response **120** closest to the correlation peak **133** is identified as the negative peak **124** of the sural response. The positive peak **126** of the sural response is the subsequent local minimum of waveform **120** and is identified by searching a pre-defined window that follows the negative peak **124**. Onset **122** is preferably determined by a combination of two methods: curvature and two-line fit. The curvature method identifies the maximum curvature point of the averaged sural nerve response **120** preceding the negative peak **124**. The two-line fit method searches for the best common point of two lines that approximate the baseline region **127** and the initial rising edge **128** of average sural nerve waveform **120**.

Of course, it should also be appreciated that other techniques well known in the art may be used to determine the nerve response onset **122**, the response negative peak **124** and the response positive peak **126**.

Once device **1** determines the nerve response onset **122**, the response negative peak **124**, and the response positive peak **126**, the device uses this information to determine (i) conduction velocity (CV), in meters per second, which is calculated as CV=(92.2/Onset), and (ii) the amplitude, in microvolts, which is calculated as the difference in amplitude between the negative peak **124** and positive peak **126**. In a preferred embodiment of the present invention (function block **176**), the CV is adjusted to compensate for the well known effect of temperature on conduction velocity before the CV is displayed on LCD **26** (FIG. **5**). More particularly, during the nerve conduction test, the skin surface temperature of the patient is measured by infrared thermometer **14** (FIG. **3**)—preferably one measurement is made with each stimulation. The overall temperature is defined as the median of the individual temperatures. If the median temperature is below 23 degrees C., then an error message is reported to the user and no nerve conduction results are displayed. If the median temperature is 30 degrees C. or greater, then no temperature compensation is performed. For temperatures between 23 and 29.5 degrees C., the CV is corrected according to the following equation:

$$CV_{Displayed}=CV_{Calculated}Q_{10}^{(\Delta T/10)}$$

where Q_{10} is a temperature coefficient and ΔT is the difference in temperature between 30 degrees C. and the median temperature. The preferred value for Q_{10} is 1.5 based on published scientific studies.

Biosensor Code Incorporated into an Adapter Interposed Between the Tail of the Biosensor and the Biosensor Port of the Testing Device

If desired, the 1-bit biosensor code (which may also be referred to as a "reuse code") may be incorporated into an adapter interposed between the tail of the biosensor and the biosensor port of the testing device, rather than being physically incorporated into the biosensor per se. In this form of the invention, the biosensor need not incorporate the traces (e.g., traces **51**F and **51**G) which are selectively connected/not connected so as to provide the 1-bit biosensor code used to detect reuse of the biosensor. Instead, the traces incorporating the 1-bit biosensor code are carried by the adapter, which also has pass-through traces for electrically connecting the working traces of the biosensor to the testing device. This form of the invention can be advantageous where it is desired to detect biosensor reuse and a biosensor does not already include the means to provide the 1-bit biosensor code.

Modifications

It should also be understood that many additional changes in the details, materials, steps and arrangements of parts, which have been herein described and illustrated in order to explain the nature of the present invention, may be made by those skilled in the art while still remaining within the principles and scope of the invention.

What is claimed is:

1. Apparatus for detecting a nerve response, the apparatus comprising:

a biosensor, the biosensor comprising:

a substrate;

a plurality of electrodes mounted to the substrate for detecting the nerve response;

a biosensor reuse code carried by the substrate for determining reuse of the biosensor, wherein the biosensor reuse code is one from a set of biosensor reuse codes, and further wherein the biosensor reuse code carried by the substrate is not unique to that biosensor; and

a control unit for detecting reuse of the biosensor when the biosensor is connected to the control unit, wherein the control unit determines the likelihood of biosensor reuse by comparing the biosensor reuse code associated with the biosensor connected to the control unit with biosensor reuse codes acquired by the control unit from previous connections between the control unit and biosensors to determine whether the biosensor reuse code of the biosensor connected to the control unit and the biosensor reuse codes acquired by the control unit from previous connections between the control unit and biosensors form a random pattern conforming with a random distribution of biosensor reuse codes.

2. Apparatus according to claim **1** wherein the biosensor reuse code is encoded on the biosensor by means of electrically passive elements.

3. Apparatus according to claim **2** wherein the passive elements comprise at least two conductive members carried by the substrate, and further wherein the biosensor reuse code is encoded by selectively connecting or not connecting the at least two conductive members.

4. Apparatus according to claim **1** further comprising a processor unit for processing the nerve response acquired by the electrodes.

5. Apparatus according to claim **4** wherein the control unit permanently disables the processor unit when the likelihood of biosensor reuse exceeds a reuse threshold.

6. Apparatus according to claim **4** wherein the control unit permanently disables the processor unit when the biosensor reuse code of the biosensor connected to the control unit and the biosensor reuse codes acquired by the control unit from previous connections between the control unit and biosensors do not form a random pattern conforming with a random distribution of biosensor reuse codes.

7. Apparatus according to claim **1** wherein the biosensor reuse code is randomly assigned to the biosensor.

8. Apparatus according to claim **1** wherein the control unit is configured to update the pattern of biosensor reuse codes with the biosensor reuse code of the biosensor currently connected to the control unit whenever a connection between a biosensor and the control unit is made.

9. A kit comprising:

a plurality of biosensors for detecting nerve responses, wherein each of the biosensors comprises a substrate, a plurality of electrodes mounted to the substrate for detecting a nerve response, and a biosensor reuse code carried by the substrate for determining reuse of the biosensor;

wherein the biosensor reuse code varies randomly among the biosensors in the kit and at least two of the biosensors in the kit share the same biosensor reuse code;

wherein each of the plurality of biosensors are configured to be connected to a control unit for detecting reuse of the biosensor when one of the plurality of biosensors is connected to the control unit;

wherein the control unit determines the likelihood of biosensor reuse by comparing the biosensor reuse code associated with the biosensor connected to the control unit with biosensor reuse codes acquired by the control unit from previous connections between the control unit and the plurality of biosensors to determine whether the biosensor reuse code of the biosensor connected to the control unit and the biosensor reuse codes acquired by the control unit from previous connections between the control unit and the plurality of biosensors form a random pattern conforming with a random distribution of biosensor reuse codes.

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