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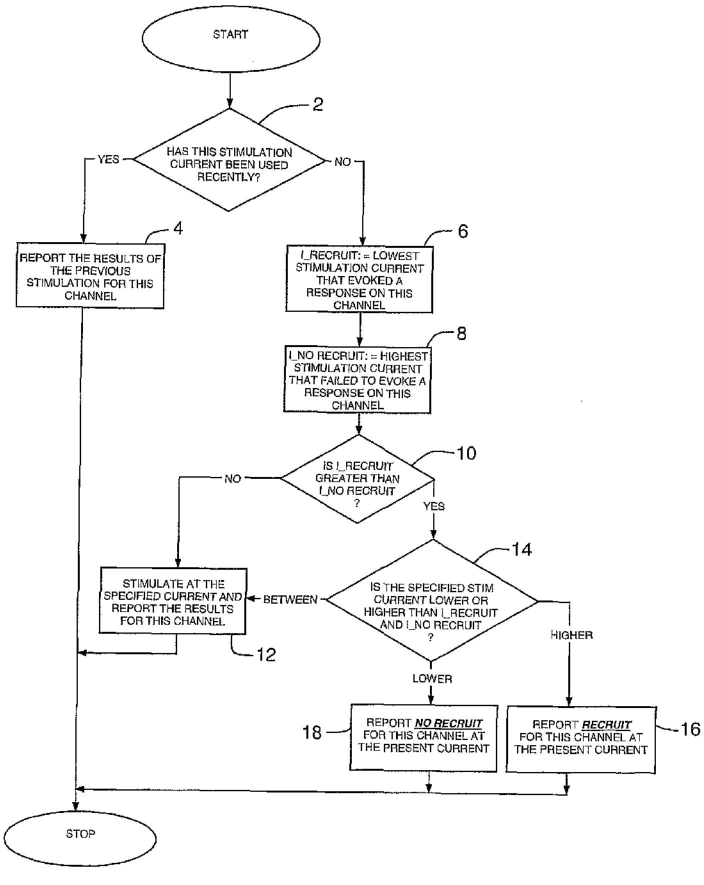
(54) Title: MULTI-CHANNEL STIMULATION THRESHOLD DETECTION ALGORITHM FOR USE IN NEUROPHYSIOLOGY MONITORING

(57) **Abstract:** The present invention relates generally to an algorithm aimed at neurophysiology monitoring, and more particularly to an algorithm capable of quickly finding stimulation thresholds over multiple channels of a neurophysiology monitoring system.



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MULTI-CHANNEL STIMULATION THRESHOLD DETECTION ALGORITHM FOR USE IN NEUROPHYSIOLOGY MONITORING

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is an international patent application claiming the benefit of priority from commonly owned and co-pending U.S. Provisional Patent Application Serial No. 60/719,897, entitled "Multi-Channel Stimulation Threshold Detection Algorithm for Use With Neurophysiology Monitoring Systems," and filed on September 22, 2005.

BACKGROUND OF THE INVENTION

Field

[0002] The present invention relates generally to an algorithm aimed at neurophysiology monitoring, and more particularly to an algorithm capable of quickly finding stimulation thresholds over multiple channels of a neurophysiology monitoring system.

Background

[0003] The risk of neurological impairment is a prime concern when performing surgical procedures in close proximity to the spine or nerves. To combat this risk, surgeons are increasingly relying on neurophysiology monitoring techniques to monitor nerves and alert them to potential impairment during a surgical procedure. Often times effective nerve monitoring requires monitoring neurophysiologic results over a multitude of channels. While this is generally advantageous, it may have the negative effect of increasing the time required to complete nerve monitoring and therefore increasing the overall surgery time as well, which in turn increases the costs and risks associated with the surgery. Based on the foregoing, a need exists for an improved means of neurophysiology monitoring, and in particular a needs exists for a means to reduce the time required to monitor neurophysiologic results over a multitude of channels. The present invention is aimed at addressing these needs.

SUMMARY OF THE INVENTION

[0004] The present invention endows surgeons with valuable information that allows for the efficient assessment of risk to neural tissue before, during, and/or after a surgical procedure. This is accomplished by quickly and accurately determining a stimulation threshold for neural tissue and relaying that information to the surgeon in a simple comprehensible fashion. Stimulation thresholds are determined by electrically stimulating nerve tissue and analyzing resulting muscle activity relative to determine the stimulation current level at which nerve tissue depolarizes. To make stimulation threshold determinations, muscle activity may be monitored by measuring electrical signals associated with muscle contraction, called electromyography ("EMG"). EMG responses can be characterized by a peak-to-peak voltage of $V_{pp} = V_{max} - V_{min}$. Characteristics of the electrical stimulation signal used may vary depending upon several factors, including the particular nerve assessment performed, the spinal target level, the type of neural tissue stimulated (e.g. nerve root, spinal cord, brain, etc...) among others.

[0005] A basic premise underlying the stimulation threshold technique is that nerves have a characteristic threshold current level (I_{thresh}) at which they will depolarize and cause a significant EMG response. A significant EMG response may be defined as having a V_{pp} greater than a predetermined threshold voltage (V_{thresh}). By way of example only, the V_{thresh} may be selected from a range including 20uV-100uV. Stimulation with a current below the threshold level, I_{thresh}, will not evoke a significant EMG response, while stimulation with a current at or above the threshold level will evoke a significant EMG response. This relationship between the stimulation current and the EMG response may be represented via a "recruitment curve." When stimulation does not evoke a significant EMG response (represented in the onset region) the stimulation current is said to have not "recruited." When stimulation does evoke a significant EMG response (represented in the linear and saturation regions) the stimulation current is said to have "recruited." I_{thresh}, is the lowest stimulation current that recruits (evokes a significant EMG response).

[0006] The algorithm described herein may considerably reduce the number of stimulations, and thus time, required to determine I_{thresh}, particularly for a number of channels, over the course of a procedure. The basic method for finding I_{thresh} utilizes a bracketing method and a bisection method. The bracketing method quickly finds a range (bracket) of stimulation currents that must contain I_{thresh} and the bisection method narrows the bracket until I_{thresh} is known within a specified accuracy.

[0007] The bracketing method adjusts the stimulation current as follows. Stimulation begins at a minimum stimulation current. Each subsequent stimulation is delivered at a current level double that of the preceding current. This doubling continues until a stimulation current results in an EMG response with a V_{pp} greater than V_{thresh}. This first stimulation current to recruit, together with the last stimulation current to have not recruited, forms the initial bracket.

[0008] After bracketing the threshold current I_{thresh}, the bisection method is used to reduce the bracket to a selected width or resolution. The stimulation current at the midpoint of the bracket is used. If the stimulation current recruits, the bracket shrinks to the lower half of the previous range. If the stimulation current does not recruit, the bracket shrinks to the upper half of the previous range. This process continues until I_{thresh} is bracketed by stimulation currents separated by the selected width or resolution. I_{thresh} is preferably defined as the midpoint of this final bracket. The bracketing and bisection steps may be repeated and I_{thresh} found for each channel unless the threshold exceeds a predetermined maximum current.

[0009] To reduce the number of stimulations required to complete the bracketing and bisection steps when I_{thresh} is determined repeatedly and/or over multiple channels, the algorithm omits stimulations for which the result is predictable from data acquired during previous stimulations. When a stimulation is omitted, the algorithm proceeds as if the stimulation had taken place. However, instead of reporting an actual recruitment result, the reported result is inferred from the previous data. This permits the algorithm to proceed to the next step immediately, without the delay associated with a stimulation. For every stimulation signal delivered, the EMG response, or lack thereof, is detected and recorded on each channel (no matter which channel is actually being processed for I_{thresh}). Later the data can be referred back to, allowing the algorithm to omit a stimulation and infer whether or not the channel would recruit at the given stimulation current.

[0010] There are two scenarios in which the algorithm may omit a stimulation and report previously obtained recruitment results. A stimulation may be omitted if the selected stimulation current would be a repeat of a previous stimulation. If the specific stimulation current is not a repeat, the stimulation may be omitted if the results are already clear from the previous data.

[0011] To determine whether to deliver an actual stimulation or omit the stimulation and report previous results, the algorithm first checks whether the selected stimulation current has been previously used. If the stimulation current has been used, the stimulation is omitted and the results of the previous stimulation are reported for the present channel. If the stimulation current has not been used, the algorithm determines $I_{recruit}$ and $I_{norecruit}$ for the present channel. $I_{recruit}$ is the lowest stimulation current that has recruited on the present channel. $I_{norecruit}$ is the highest stimulation current that has failed to recruit on the present channel. If $I_{recruit}$ is not greater than $I_{norecruit}$, the algorithm will stimulate at the selected current and report the results for the present channel. If $I_{recruit}$ is greater than $I_{norecruit}$, the algorithm identifies whether the selected stimulation current is higher than $I_{recruit}$, lower than $I_{norecruit}$, or between $I_{recruit}$ and $I_{norecruit}$. If the selected stimulation current is higher than $I_{recruit}$, the algorithm omits the stimulation and reports that the present channel recruits at the specified current. Conversely, when the selected stimulation current is lower than $I_{norecruit}$, the algorithm infers that the present channel will not recruit at the selected current and reports that result. If the selected stimulation current falls between $I_{recruit}$ and $I_{norecruit}$, the result of the stimulation cannot be inferred. The algorithm stimulates at the selected current and reports the results for the present channel. This method may be repeated until I_{thresh} has been determined for every active channel.

[0012] The order in which channels are processed is immaterial. The channel processing order may be biased to yield the highest or lowest threshold first or an arbitrary processing order may be used. It is also not necessary to complete the algorithm for one channel before beginning to process the next channel. Channels are still processed one at a time, however, the algorithm may cycle between one or more channels, processing as few as one stimulation current for that channel before moving on to the next channel. In this manner the algorithm may advance all channels essentially together and bias the order to find the lower threshold channels first or the higher threshold channels first.

[0013] To further reduce the number of stimulations required to repeatedly find I_{thresh} over the course of a procedure, the algorithm includes a confirmation step. If I_{thresh} has been previously determined for a specific channel, the algorithm may simply confirm that I_{thresh} has not changed rather than beginning anew with the bracketing and bisection methods. The algorithm first determines whether it is conducting the initial threshold determination for the channel or whether there is a previous I_{thresh} determination. If it is not the initial determination, the algorithm confirms the previous determination. If the previous threshold is confirmed, the algorithm reports that value as the present I_{thresh}. If it is the initial I_{thresh} determination or if the previous threshold cannot be confirmed, the algorithm enters the bracketing and bisection states to determine I_{thresh} and then reports the value.

[0014] The confirmation step attempts to ascertain whether I_{thresh} has moved from its last known value. To do this, the algorithm applies two stimulation currents, one at or just above the threshold value and one just below the threshold value. If the stimulation at or above I_{thresh} recruits and the stimulation just below I_{thresh} does not recruit, then I_{thresh} is confirmed and the algorithm may report the initial value again as I_{thresh} and proceed to process another channel. If the stimulation just below I_{thresh} recruits, it may be concluded that I_{thresh} has decreased and likewise, if the stimulation at or just above I_{thresh} fails to recruit, it may be assumed that I_{thresh} has increased and therefore I_{thresh} cannot be confirmed.

[0015] If I_{thresh} cannot be confirmed, the algorithm enters the bracketing state. Rather than beginning the bracketing state from the minimum stimulation current, however, the bracketing state may begin from the previous I_{thresh}. The bracketing may advance up or down depending on whether I_{thresh} has increased or decreased. When the algorithm enters the bracketing state, the increment used in the confirmation step is exponentially doubled until the channel recruits, at which time it enters the bisection state. The confirmation step may be performed for each channel, in turn, in any order. Again stimulations may be omitted and the algorithm may begin processing a new channel before completing the algorithm for another channel, as described above.

[0016] The algorithm described herein may be particularly useful when employed to monitor nerve pathology in conjunction with the use of a nerve retractor. A typical nerve retractor serves to pull or otherwise maintain a nerve outside the surgical corridor, thereby protecting the nerve from inadvertent damage or contact by the "active" instrumentation used to perform the actual surgery. While generally advantageous, it has been observed that such retraction can cause nerve function to become impaired or otherwise pathologic over time due to the retraction. Monitoring I_{thresh} during nerve retraction may be useful to assess the degree to which retraction of a nerve or neural structure affects the nerve function over time. One advantage of such monitoring is that the conduction of the nerve may be monitored during the procedure to determine whether the neurophysiology and/or function of the nerve changes (for the better or worse) as a result of the particular surgical procedure. For example, it may be observed that the nerve conduction decreases (indicated by an increase in I_{thresh} over time) during the retraction, indicating that the nerve function has been negatively affected. In contrast, the nerve conduction may increase (indicated by a decrease in I_{thresh} over time), indicating that the nerve function may have been restored or improved by the surgical procedure (such as during a successful decompression surgery, etc...). As mentioned, a change in I_{thresh} may occur on any channel; therefore it is advantageous to calculate the actual I_{thresh} for each channel, as opposed to determining a value for just the channel with the highest or lowest I_{thresh}. The algorithm of the present invention accomplishes this while substantially limiting the number of stimulations required to do so. This may substantially reduce the time required to make an I_{thresh} determination which in turn may reduce the overall surgical time and risk to the patient.

[0017] The algorithm of the present invention may also be of particular use during Motor Evoked Potential (MEP) monitoring. When surgical procedures are performed in the proximity of the spinal cord, potential damage to the spinal cord is a paramount concern. Consequences of spinal cord damage may range from a slight loss of sensation to complete paralysis of the extremities, depending on the location and extent of damage. MEP monitoring, which generally involves monitoring the transmission of an electrical signal along the spinal cord, may be employed to assess the spinal cord before, during, and/or after surgery. Degradation or decreased conduction of an electrical signal, indicated by an increase in I_{thresh}, may indicate that the health of the spinal cord is compromised. Obtaining such information quickly may allow the surgeon to initiate corrective measures before the damage gets worse and/or becomes permanent. Similar to the nerve pathology monitoring mentioned above, changes in I_{thresh} indicating potential damage to the spinal cord may occur on any monitored channel, thus it is advantageous to calculate the actual I_{thresh} for each channel, as opposed to determining just the channel with the highest or lowest I_{thresh}. Employing the algorithm of the present invention again allows this to be done accurately and efficiently.

[0018] The algorithm of the present invention may be employed for use on any of a number of neurophysiology monitoring systems. By way of example only, a preferred multi-channel neurophysiology monitoring system for employing the algorithm of the present invention to quickly find stimulation thresholds for a multitude of channels may be capable of carrying out neurophysiologic assessment functions including, but not necessarily limited to, Twitch Test (neuromuscular pathway assessment), Screw Test (pedicle integrity testing), Detection (nerve proximity testing during surgical access), Nerve Retractor (nerve pathology monitoring), MEP (Motor Evoked Potential spinal cord monitoring), and SSEP (Somatosensory Evoked Potential spinal cord monitoring).

[0019] The surgical system includes a control unit, a patient module, an MEP stimulator, an EMG harness, including eight pairs of EMG electrodes and a return (anode) electrode coupled to the patient module, at least one pair of stimulation electrodes coupled to the MEP stimulator, and a host of surgical accessories (including but not limited to a nerve retractor, screw test probe, dynamic stimulation clips, a K-wire, one or more dilating cannula, and a tissue retraction assembly) capable of being coupled to the patient module via one or more accessory cables. Information generated by the system is shown on a screen display and may include, but is not necessarily limited to, alpha-numeric and/or graphical information regarding MEP, nerve pathology, myotome/EMG levels, stimulation levels, the function selected.

[0020] Neural pathology monitoring may be performed by electrically stimulating a nerve root according to the hunting algorithm, via one or more stimulation electrodes at the distal end of the nerve root retractor and monitoring each channel for corresponding evoked muscle responses. Threshold hunting continues according to the algorithm until I_{thresh} is determined for each channel in range. A pathology assessment is made by determining a baseline stimulation threshold with direct contact between the nerve retractor and the nerve, prior to retraction. Subsequent stimulation thresholds are determined during retraction and they are compared to the baseline threshold. An increase in I_{thresh} over time is an indication that the nerve function is deteriorating and retraction should be reduced or stopped altogether to prevent permanent damage. A decrease in I_{thresh} over time may be an indication that nerve function has been at least partially restored. The display of I_{thresh} values may be accompanied by a color code making use of the colors Red, Yellow, and Green to indicate predetermined unsafe, intermediate and safe levels, respectively.

[0021] MEP may be performed by electrically stimulating the motor cortex of the brain with electrical stimulation signals which creates an action potential that travels along the spinal cord and into the descending nerves, evoking activity from muscles innervated by the nerves. EMG responses of the muscles are recorded by the system and analyzed in relation to the stimulation signal. The multi-channel threshold hunting algorithm described above may be utilized to determine a baseline I_{thresh} for each channel. Having determined a baseline I_{thresh} for each channel, subsequent monitoring may be performed as desired throughout the procedure and recovery period to obtain updated I_{thresh} values for each channel. Each new determination of I_{thresh} is compared by the surgical system to the baseline I_{thresh} for the appropriate channel. The difference (ΔI_{thresh}) between the baseline I_{thresh} and the new I_{thresh} is calculated and the ΔI_{thresh} value is compared to predetermined "safe" and "unsafe" values. The display of I_{thresh} may be accompanied by a color code making use of the colors Red, Yellow, and Green to indicate predetermined unsafe, intermediate and safe levels, respectively.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] Many advantages of the present invention will be apparent to those skilled in the art with a reading of this specification in conjunction with the attached drawings, wherein like reference numerals are applied to like elements and wherein:

[0023] Figure 1 is a graph illustrating a plot of the neuromuscular response (EMG) of a given myotome over time based on a current stimulation pulse applied to a nerve bundle coupled to the given myotome;

[0024] Figure 2 is a graph illustrating a plot of a stimulation signal capable of producing a neuromuscular response (EMG) of the type shown in FIG. 1;

[0025] Figure 3 is a graph illustrating a plot of another embodiment of a stimulation signal capable of producing a neuromuscular response (EMG) of the type shown in FIG. 1;

[0026] Figure 4 is a graph illustrating a plot of peak-to-peak voltage (V_{pp}) for each given stimulation current level (I_{Stim}) forming a stimulation current pulse train according to the present invention (otherwise known as a "recruitment curve");

[0027] Figures 5A - 4D are graphs illustrating the foundation of a rapid multi-channel current threshold-hunting algorithm according to one aspect of the present invention;

[0028] Figure 6 is a flowchart illustrating the method by which the algorithm determines whether to perform or omit a stimulation according to one aspect of the present invention;

[0029] Figures 7A - 7C are graphs illustrating use of the threshold hunting algorithm of FIG. 5 and further omitting stimulations when the likely result is already clear from previous data according to one aspect of the present invention;

[0030] Figure 8 is a flowchart illustrating the sequence employed by the algorithm to determine and monitor I_{thresh} according to one aspect of the present invention;

[0031] Figure 9 is a graph illustrating the confirmation step employed by the algorithm to determine whether I_{thresh} has changed from a previous determination according to one aspect of the present invention;

[0032] Figure 10 is a perspective view of an exemplary surgical system 40 capable of employing the algorithm of the present invention to monitor I_{thresh} over a multitude of channels;

[0033] Figure 11 is a block diagram of the surgical system 40 shown in FIG. 10;

[0034] Figure 12 is an exemplary screen display illustrating one embodiment of a nerve pathology monitoring function of the surgical system 40 utilizing the algorithm of the present invention to determine I_{thresh}; and

[0035] Figure 13 is an exemplary screen display illustrating one embodiment of a transcranial motor evoked potential monitoring function of the surgical system 40 utilizing the algorithm of the present invention to determine I_{thresh}.

DESCRIPTION OF THE PREFERRED EMBODIMENT

[0036] Illustrative embodiments of the invention are described below. In the interest of clarity, not all features of an actual implementation are described in this specification. It will of course be appreciated that in the development of any such actual embodiment, numerous implementation-specific decisions must be made to achieve the developers' specific goals, such as compliance with system-related and business-related constraints, which will vary from one implementation to another. Moreover, it will be appreciated that such a development effort might be complex and time-consuming, but would nevertheless be a routine undertaking for those of ordinary skill in the art having the benefit of this disclosure. The methods disclosed herein boast a variety of inventive features and components that warrant patent protection, both individually and in combination.

[0037] The present invention endows surgeons with valuable information that allows for the efficient assessment of risk to neural tissue before, during, and/or after a surgical procedure. This is accomplished by quickly and accurately determining a stimulation threshold for neural tissue and relaying that information to the surgeon in a simple comprehensible fashion. Stimulation thresholds are determined by electrically stimulating nerve tissue and analyzing resulting muscle activity relative to determine the stimulation current level at which nerve tissue depolarizes. To make stimulation threshold determinations, muscle activity may be monitored by measuring electrical signals associated with muscle contraction, called electromyography ("EMG"). EMG responses, such as that represented in FIG. 1, can be characterized by a peak-to-peak voltage of $V_{pp} = V_{max} - V_{min}$. Characteristics of the electrical stimulation signal used may vary depending upon several factors including, the particular nerve assessment performed, the spinal target level, the type of neural tissue stimulated (e.g. nerve root, spinal cord, brain, etc…) among others. By way of example, a single pulse stimulation signal (such as that illustrated by way of example in FIG. 2) or a multi-pulse stimulation signal (such as that illustrated by way of example in FIG. 3) may be used.

[0038] A basic premise underlying the stimulation threshold technique is that nerves have a characteristic threshold current level (I_{thresh}) at which they will depolarize and cause a significant EMG response. A significant EMG response may be defined as having a V_{pp} greater than a predetermined threshold voltage (V_{thresh}), such as, by way of example only, 100μV. Stimulation with a current below the threshold level, I_{thresh}, will not evoke a significant EMG response, while stimulation with a current at or above the threshold level will evoke a significant EMG response. This relationship between the stimulation current and the EMG response may be represented via a "recruitment curve," such as that illustrated in FIG. 4. When stimulation does not evoke a significant EMG response (represented in the onset region), the stimulation current is said to have not "recruited." When stimulation does evoke a significant EMG response (represented in the linear and saturation regions), the stimulation current is said to have "recruited." The stimulation threshold, I_{thresh}, is the lowest stimulation current that recruits (evokes a significant EMG response).

[0039] Knowing I_{thresh} allows the surgeon to make various useful assessments regarding the safety of nerves during a surgical procedure. For example, it is often necessary to move or maintain a nerve outside of the surgical area using a nerve retractor. While retraction is generally necessary to provide better access to the surgical area and protect the nerve from inadvertent damage (e.g. through contact with various surgical implements), over time such retraction may impair nerve. A decrease in nerve function is likely to be accompanied by a corresponding increase in I_{thresh} as a greater stimulation will be required to depolarize the nerve.

Thus, by monitoring for changes in I_{thresh} over the course of retraction, the surgeon may be alerted to potential danger and take steps to correct the condition (e.g. such as releasing or reducing pressure on the nerve) before nerve impairment gets worse and/or becomes permanent.

[0040] In many cases, to effectively utilize the valuable information I_{thresh} provides, I_{thresh} must be determined frequently and for a number of different channels (corresponding to different EMG recording sites and the muscles they monitor) because I_{thresh} may vary between channels. Additionally, changes in I_{thresh} (indicating a potential problem) may occur independently on one channel and not another, thereby necessitating repeated determinations over multiple channels in order to gain the maximum benefit. Numerous stimulations may potentially be required to make a single I_{thresh} determination and making I_{thresh} determinations for multiple channels significantly increases this potential. For each stimulation signal emitted, a certain period of time (equaling the signal duration plus nerve recovery time) is exhausted. Over a number of stimulations this time adds up, such that the surgeon may experience a lag time upwards of 30 seconds or longer between initiating a test and receiving the I_{thresh} for each channel. Added over an entire procedure this may amount to a significant increase in surgery time and/or cause a reluctance to monitor altogether.

[0041] The algorithm described herein may considerably reduce the number of stimulations, and thus time, required to determine I_{thresh}. This reduction may be especially evident when determining I_{thresh} over every channel of a multi-channel neurophysiology monitoring system, such as that described below. FIGS. 5A-5D illustrate the fundamental steps of a threshold hunting algorithm used to quickly and accurately determine I_{thresh}. I_{thresh} is, once again, the minimum stimulation current (I_{stim}) that results in an EMG response with a V_{pp} greater than a predetermined threshold voltage, V_{thresh}. The basic method for finding I_{thresh} utilizes a combination of a bracketing method and a bisection method. The bracketing method quickly finds a range (bracket) of stimulation currents that must contain I_{thresh} and the bisection method narrows the bracket until I_{thresh} is known within a specified accuracy. If I_{thresh} on a given channel exceeds a predetermined maximum stimulation current, that threshold is considered out of range.

[0042] To find the initial bracket, the bracketing method adjusts the stimulation current as follows. Stimulation begins at a predetermined minimum stimulation current. The minimum stimulation current depends upon the selected function, by way of example only, the minimum stimulation current used for nerve pathology monitoring may be 1.0mA while the minimum stimulation current used for MEP monitoring may be 60mA. Each subsequent stimulation is delivered at a current level double that of the preceding current. This exponential doubling continues until a stimulation current results in an EMG response with a V_{pp} greater than V_{thresh} (i.e. it recruits). This first stimulation current to recruit, together with the last stimulation current to have not recruited, forms the initial bracket, as illustrated in FIG. 5B.

[0043] With respect to FIGS. 5C and 5D, after bracketing I_{thresh}, the bisection method is used as follows to reduce the bracket to a selected width, shown here by way of example only as 0.1mA. Bracketing begins by stimulating with a current at the midpoint of the initial bracket. If the stimulation current recruits, the bracket shrinks to the lower half of the previous range. If the stimulation current does not recruit, the bracket shrinks to the upper half of the previous range. This process continues until I_{thresh} is bracketed by stimulation currents separated by the selected width or resolution, 0.1mA in this example. I_{thresh} may be defined as any point falling within the final bracket such as for example, the midpoint of the bracket, the upper end of the bracket, and the lower end of the bracket. The bracketing and bisection steps may be repeated for all channels until I_{thresh} is determined for each one.

[0044] Significantly, the algorithm further operates to reduce the number of actual stimulations required to complete bracketing and bisection when I_{thresh} is determined repeatedly and/or over multiple channels. The algorithm does so by omitting stimulations for which the result is predictable from data acquired during previous stimulations. When a stimulation is omitted, the algorithm proceeds as if the stimulation had taken place. Instead of reporting an actual recruitment result, however, the reported result is inferred from the previous data. This permits the algorithm to proceed to the next step immediately, without the delay associated with a stimulation.

[0045] For every stimulation signal delivered, the EMG response, or lack thereof, is detected and recorded on each channel, no matter which channel is actually being processed for I_{thresh}. That is, every channel either recruits or does not recruit (again, a channel is said to have recruited if a stimulation signal evokes a significant EMG response from the muscle associated with that channel) in response to a given stimulation signal. These recruitment results are detected and saved for each channel. Later, when a different channel is processed for I_{thresh}, the saved data can be referred back to such that the algorithm may omit a stimulation if it may infer whether or not the channel would recruit at the given stimulation current.

[0046] There are two scenarios in which the algorithm may omit a stimulation and report previously obtained recruitment results. A stimulation may be omitted if the selected stimulation current would be a repeat of a previous stimulation. By way of example only, if a stimulation at 1.0mA was performed to determine I_{thresh} for one channel, and a stimulation at 1.0mA is later required to determine I_{thresh} for another channel, the algorithm may omit the stimulation and report the previous results. If the specific stimulation current required has not previously been used, a stimulation may still be omitted if the results are already clear from the previous data. By way of example only, if a stimulation at 2.0mA was performed to determine I_{thresh} for a previous channel and the present channel did not recruit, when a stimulation at 1.0 mA is later required to determine I_{thresh} for the present channel, the algorithm may infer that the present channel will not recruit at 1.0 mA since it did not recruit at 2.0mA. The algorithm may omit the stimulation and report the previous result.

[0047] FIG. 6 illustrates (in flowchart form) a method by which the algorithm determines whether to deliver an actual stimulation or omit the stimulation and report previous results. The algorithm first determines if the selected stimulation current has been previously used (step 2). If the stimulation current has been used, the stimulation is omitted and the results of the previous stimulation are reported for the present channel (step 4). If the stimulation current has not been used, the algorithm determines $I_{recruit}$ (step 6) and $I_{norecruit}$ (step 8) for the present channel. $I_{recruit}$ is the lowest stimulation current that has recruited on the present channel. $I_{norecruit}$ is the highest stimulation current that has failed to recruit on the present channel. Next the algorithm determines if $I_{recruit}$ is greater than $I_{norecruit}$ (step 10). An $I_{recruit}$ that is less than or equal to $I_{norecruit}$

is indicative of a changing I_{thresh}. Thus, previous results are not likely reflective of the present threshold state and the algorithm will not use them to infer a response to a given stimulation current. The algorithm will stimulate at the selected current and report the results for the present channel (step 12). If $I_{recruit}$ is greater than $I_{norecruit,}$ the algorithm next identifies whether the selected stimulation current is higher than $I_{recruit}$, lower than $I_{norecruit}$, or between $I_{recruit}$ and $I_{norecruit}$ (step 14). If the selected stimulation current is higher than $I_{recruit,}$ the algorithm omits the stimulation and reports that the present channel recruits at the specified current (step 16). Conversely, when the selected stimulation current is lower than $I_{norecruit,}$ the algorithm infers that the present channel will not recruit at the selected current and reports that result (step18). If the selected stimulation current falls between $I_{recruit}$ and $I_{norecruit,}$ the result of the stimulation cannot be inferred. The algorithm stimulates at the selected current and reports the results for the present channel (step 12). This method may be repeated until I_{thresh} has been determined for every active channel.

[0048] For the purposes of example only, FIGS. 7A-7C demonstrate use of the algorithm of the present invention to determine I_{thresh} on two channels. It should be appreciated, however, that the algorithm of the present invention is not limited to finding I_{thresh} for two channels but may be used to find I_{thresh} for any number of channels. It should also be appreciated that the current levels used herein are for exemplary purposes only and the current levels utilized during an actual implementation may vary considerably from very low currents (e.g. 0.1mA) to very high currents (e.g. 1000mA), depending upon a number of factors, including, but not necessarily limited to, the function being performed and individual patient characteristics, among others. With reference to FIG. 7A, channel 1 has an I_{thresh} to be found of 12.5mA and channel 2 has an I_{thresh} to be found of 8.5mA. I_{thresh} for channel 1 is found first, using the bracketing and bisection methods discussed above, as illustrated in FIG. 7B. Bracketing begins at the minimum stimulation current (for the purposes of example only) of 1mA. As this is the first channel processed and no previous recruitment results exist, no stimulations are omitted. The stimulation current is doubled with each successive stimulation (i.e. 1mA → 2mA → 4mA → 8mA → 16mA) until a significant EMG response is finally evoked at 16mA. The initial bracket of 8mA-16mA is bisected, using the bisection method described above (i.e. 12mA (midpoint of initial bracket) → 14mA (midpoint of bracket 2) → 13mA (midpoint of bracket 3)), until the stimulation threshold is determined to be 12.5mA, the midpoint of the final bracket. Having found I_{thresh} on channel 1, the algorithm may turn to channel 2, as illustrated in FIG. 7C. The algorithm begins to process channel 2 by determining the initial bracket, which is again 8mA-16mA. In doing so, the algorithm refers back to the data obtained for channel 2 during channel 1 processing. All the stimulation currents required in the bracketing state were used in determining I_{thresh} for channel 1. From the data gathered during channel 1 processing, the algorithm infers that channel 2 will not recruit at stimulation currents of 1, 2, 4, and 8mA and will recruit at 16mA. These stimulations are omitted and the inferred results are reported in turn.

[0049] The first stimulation current selected in the bisection state, 12mA, was used previously and the algorithm may omit the stimulation and report that channel 2 recruits at that stimulation current. The next stimulation current selected in the bisection phase, 10mA, was not previously used and the algorithm must therefore determine whether the result of a stimulation at 10mA may still be inferred. $I_{recruit}$ and $I_{norecruit}$ are determined to be 12mA and 8mA respectively. 10mA lies in between the $I_{recruit}$ value of 12mA and $I_{norecruit}$ value of 8mA, thus the result may not be inferred from the previous data and the stimulation may not be omitted. The algorithm stimulates at 10mA and reports that the channel recruits. The bracket shrinks to the lower half, making 9mA the next stimulation current. 9mA has not previously been used so the algorithm again determines $I_{recruit}$ and $I_{norecruit}$, now 10mA and 8mA respectively. The selected stimulation current, 9mA, falls inbetween $I_{recruit}$ and $I_{norecruit}$, thus, the algorithm stimulates at 9mA and reports the results. The bracket now stands at its final width of 1mA (for the purposes of example only) and the midpoint of the bracket, 8.5mA, is selected and reported as I_{thresh} for channel 2. It should again be appreciated that the midpoint of the bracket is selected as I_{thresh} for exemplary purposes and I_{thresh} could be reported as any value within the final bracket, such as for example, the upper end of the bracket or the lower end of the bracket.

[0050] Although the algorithm is discussed and shown to process channels in numerical order, it will be understood that the actual order in which channels are processed is immaterial. The channel processing order may be biased to yield the highest or lowest threshold first (discussed below) or an arbitrary processing order may be used. Furthermore, it will be understood that it is not necessary to complete the algorithm for one channel before beginning to process the next channel. Channels are still processed one at a time, however, the algorithm may cycle between one or more channels, processing as few as one stimulation current for that channel before moving on to the next channel. By way of example only, the algorithm may stimulate at 1mA while processing a first channel for I_{thresh}. Before stimulating at 2mA (the next stimulation current in the bracketing phase) the algorithm may cycle to any other channel and process it for the 1mA stimulation current (omitting the stimulation if applicable). Any or all of the channels may be processed this way before returning to the first channel to apply the next stimulation. Likewise, the algorithm need not return to the first channel to stimulate at 2mA, but instead may select a different channel to process first at the 2mA level. In this manner, the algorithm may advance all channels essentially together and bias the order to find the lower threshold channels first or the higher threshold channels first. By way of example only, the algorithm may stimulate at one current level and process each channel in turn at that level before advancing to the next stimulation current level. The algorithm may continue in this pattern until the channel with the lowest I_{thresh} is bracketed. The algorithm may then process that channel exclusively until I_{thresh} is determined, and then return to processing the other channels one stimulation current level at a time until the channel with the next lowest I_{thresh} is bracketed. This process may be repeated until I_{thresh} is determined for each channel in order of lowest to highest I_{thresh}. Should I_{thresh} for more than one channel fall within the same bracket, the bracket may be bisected, processing each channel within that bracket in turn until it becomes clear which one has the lowest I_{thresh}. If it becomes more advantageous to determine the highest I_{thresh} first, the algorithm may continue in the bracketing state until the bracket is found for every channel and then bisect each channel in descending order.

[0051] In another significant aspect of the present invention, to further reduce the number of stimulations required to repeatedly find I_{thresh} over the course of a procedure, the algorithm includes a confirmation step. If I_{thresh} has been previously determined for a specific channel, the algorithm may simply confirm that I_{thresh} has not changed rather than beginning anew with the bracketing and bisection methods. FIG. 8 illustrates the overall sequence the algorithm follows to determine I_{thresh}. The algorithm first determines whether it is conducting the initial threshold determination, for the channel or whether there is a previous I_{thresh} determination (step 20). If it is not the initial determination the algorithm confirms the previous determination (step 22), as described below. If the previous threshold is confirmed, the algorithm reports that value as the present I_{thresh} (step 24). If it is the initial I_{thresh} determination, or if the previous threshold cannot be confirmed, the algorithm enters the bracketing (step 26) and bisection (step 28) states to determine I_{thresh} and then reports the value (step 24).

[0052] FIG. 9 illustrates, by way of example only, a method employed by the algorithm for confirming a previous threshold, I_{thresh}. The confirmation step attempts to ascertain whether I_{thresh} has moved from its last known value. To do this, the algorithm applies two stimulation currents, one at or just above the threshold value and one just below the threshold value. If the stimulation at or above I_{thresh} recruits and the stimulation just below I_{thresh} does not recruit, then I_{thresh} is confirmed and the algorithm may report the initial value again as I_{thresh} and proceed to process another channel. If the stimulation just below I_{thresh} recruits, it may be concluded that I_{thresh} has decreased and likewise, if the stimulation at or just above I_{thresh} fails to recruit, it may be assumed that I_{thresh} has increased and therefore I_{thresh} can not be confirmed.

[0053] If I_{thresh} cannot be confirmed, the algorithm enters the bracketing state. Rather than beginning the bracketing state from the minimum stimulation current, however, the bracketing state may begin from the previous I_{thresh}. The bracketing may advance up or down depending on whether I_{thresh} has increased or decreased. By way of example only, if the previous value of I_{thresh} was 4mA, the confirmation step may stimulate at 4mA and 3.8mA. If the stimulation at 4mA fails to evoke a significant response, it may be concluded that the I_{thresh} has increased and the algorithm will bracket upwards from 4mA. When the algorithm enters the bracketing state, the increment used in the confirmation step (i.e. 0.2mA in this example) is doubled. Thus the algorithm stimulates at 4.4mA. If the channel fails to recruit at this current level, the increment is doubled again to 0.8mA, and the algorithm stimulates at 5.2mA. This process is repeated until the maximum stimulation current is reached or the channel recruits, at which time it may enter the bisection state.

[0054] If, during the confirmation step, the stimulation current just below the previously determined I_{thresh} recruits, it may be concluded that I_{thresh} for that channel has decreased and the algorithm may bracket down from that value (i.e. 3.8mA in this example). Thus, in this example the algorithm would double the increment to 0.4 mA and stimulate at 3.4mA. If the channel still recruits at this stimulation current, the increment is doubled again to 0.8mA such that the algorithm stimulates at 2.6mA. This process is repeated until the minimum stimulation current is reached, or the channel fails to recruit, at which time the algorithm may enter the bisection state. The confirmation step may be performed for each channel, in turn, in any order. Again stimulations may be omitted and the algorithm may begin processing a new channel before completing the algorithm for another channel, as described above.

[0055] By way of example only, the algorithm of the present invention may be particularly useful when employed to monitor nerve pathology in conjunction with the use of a nerve retractor, such as nerve retractor 60 and 61 (shown in FIG. 10). A typical nerve retractor serves to pull or otherwise maintain a nerve outside the surgical corridor, thereby protecting the nerve from inadvertent damage or contact by the “active” instrumentation used to perform the actual surgery. While generally advantageous, it has been observed that such retraction can cause nerve function to become impaired or otherwise pathologic over time due to the retraction. Monitoring I_{thresh} during nerve retraction may be useful to assess the degree to which retraction of a nerve or neural structure affects the nerve function over time. One advantage of such monitoring is that the conduction of the nerve may be monitored during the procedure to determine whether the neurophysiology and/or function of the nerve changes (for the better or worse) as a result of the particular surgical procedure. For example, it may be observed that the nerve conduction decreases (indicated by an increase in I_{thresh} over time) during the retraction, indicating that the nerve function has been negatively affected. In contrast, the nerve conduction may increase (indicated by a decrease in I_{thresh} over time), indicating that the nerve function may have been restored or improved by the surgical procedure (such as during a successful decompression surgery, etc…). As mentioned, a change in I_{thresh} may occur on any channel; therefore it is advantageous to calculate the actual I_{thresh} for each channel, as opposed to determining a value for just the channel with the highest or lowest I_{thresh}. The algorithm of the present invention accomplishes this while substantially limiting the number of stimulations required to do so. This may substantially reduce the time required to make an I_{thresh} determination which in turn may reduce the overall surgical time and risk to the patient.

[0056] By way of example only, the algorithm of the present invention may also be of particular use during Motor Evoked Potential (MEP) monitoring. When surgical procedures are performed in the proximity of the spinal cord, potential damage to the spinal cord is a paramount concern. Consequences of spinal cord damage may range from a slight loss of sensation to complete paralysis of the extremities, depending on the location and extent of damage. MEP monitoring, which generally involves monitoring the transmission of an electrical signal along the spinal cord, may be employed to assess the spinal cord before, during, and/or after surgery. Degradation or decreased conduction of an electrical signal, indicated by an increase in I_{thresh}, may indicate that the health of the spinal cord is compromised. Obtaining such information quickly may allow the surgeon to initiate corrective measures before the damage gets worse and/or becomes permanent. Similar to the nerve pathology monitoring mentioned above, changes in I_{thresh} indicating potential damage to the spinal cord may occur on any monitored channel, thus it is advantageous to calculate the actual I_{thresh} for each channel, as opposed to determining just the channel with the highest or lowest I_{thresh}. Employing the algorithm of the present invention again allows this to be done accurately and efficiently.

[0057] The algorithm of the present invention may be employed for use on any of a number of neurophysiology monitoring systems, including but not limited to that shown and described in commonly owned Int'l Patent App. No. PCT/US02/30617, entitled "System and Methods for Performing Surgical Procedures and Assessments," filed on Sept. 25, 2002; and Int'l Patent App. No. PCT/US2006/003966, entitled "System and Methods for Performing Neurophysiologic Assessments During Spine Surgery," filed on February 2, 2006, both of which are hereby incorporated by reference as if set forth fully herein. FIG. 10 illustrates, by way of example only, a multi-channel neurophysiology monitoring system for employing the algorithm of the present invention to quickly find stimulation thresholds for a multitude of channels. By way of example only, the neuromonitoring system 40 may be capable of carrying out neurophysiologic assessment functions including, but not necessarily limited to, Twitch Test (neuromuscular pathway assessment), Screw Test (pedicle integrity testing), Detection (nerve proximity testing during surgical access), Nerve Retractor (nerve pathology monitoring), MEP (Motor Evoked Potential spinal cord monitoring), and SSEP (Somatosensory Evoked Potential spinal cord monitoring). It is expressly noted that, although described herein largely in terms of use in spinal surgery, the neuromonitoring system 10 and related methods of the present invention are suitable for use in any number of additional surgical procedures where neurological impairment is a concern.

[0058] The surgical system 40 includes a control unit 42, a patient module 44, an MEP stimulator 46, an EMG harness 48, including eight pairs of EMG electrodes 50 and a return (anode) electrode 52 coupled to the patient module 44, at least one pair of stimulation electrodes 54 coupled to the MEP stimulator 46, and a host of surgical accessories 56 capable of being coupled to the patient module 44 via one or more accessory cables 58. The surgical accessories 56 may include, but are not necessarily limited to, a neural pathology monitoring device such as nerve root retractors 60 and 62. Additional surgical accessories may include stimulation accessories (such as a screw test probe 70 and dynamic stimulation clips 72, 74), surgical access components (such as a K-wire 76, one or more dilating cannulae 78, 80, and a tissue retraction assembly 82).

[0059] FIG. 11 is a block diagram of the surgical system 40, the operation of which will be explained in conjunction with FIG. 10. The control unit 42 includes a touch screen display 64 and a base 66, which collectively contain the essential processing capabilities for controlling the surgical system 40. The touch screen display 64 is preferably equipped with a graphical user interface (GUI) capable of graphically communicating information to the user and receiving instructions from the user. The base 66 contains computer hardware and software that commands the stimulation sources (e.g. MEP stimulator 46 and patient module 44) receives digital and/or analog signals and other information from the patient module 44, processes the EMG responses, and displays the processed data to the operator via the display 64. The primary functions of the software within the control unit 42 include receiving user commands via the touch screen display 64, activating stimulation in a requested mode (e.g. Screw Test (Basic, Difference, Dynamic), Detection, Nerve Retractor, MEP, SSEP, Twitch Test), processing signal data according to defined algorithms (described below), displaying received parameters and processed data, and monitoring system status.

[0060] The patient module 44 is connected via a data cable 67 to the control unit 42, and contains the electrical connections to electrodes, signal conditioning circuitry, stimulator drive and steering circuitry, and a digital communications interface to the control unit 42. In use, the control unit 42 is situated outside but close to the surgical field (such as on a cart adjacent the operating table) such that the display 64 is directed towards the surgeon for easy visualization. The patient module 44 may be located near the patient's legs or may be affixed to the end of the operating table at mid-leg level using a bedrail clamp. The position selected should be such that all EMG electrodes can reach their farthest desired location without tension during the surgical procedure. The information displayed to the user on the display 62 may include, but is not necessarily limited to, alpha-numeric and/or graphical information regarding MEP, nerve pathology, myotome/EMG levels, stimulation levels, the function selected, and the instrument in use.

[0061] In a preferred embodiment, EMG response monitoring for the system 40 is accomplished via 8 pairs of EMG electrodes 50 placed on the skin over the muscle groups to be monitored, a common electrode 51 providing a ground reference to pre-amplifiers in the patient module 44, and an anode electrode 52 providing a return path for the stimulation current. The EMG responses provide a quantitative measure of the nerve depolarization caused by the electrical stimulus. It should be appreciated that any of a variety of known electrodes can be employed with system 40, including but not limited to surface pad electrodes and needle electrodes. An exemplary EMG electrode is the dual surface electrode shown and described in detail in the commonly owned and co-pending US Patent App. Ser. No. 11,048,404, entitled "Improved Electrode System and Related Methods," filed on January 31, 2005, which is expressly incorporated by reference into this disclosure as if set forth in its entirety herein.

[0062] The arrangement of EMG electrodes depends on a multitude of factors, including for example, the spinal cord level, neural tissue at risk, and user preference, among others. In one embodiment (set forth by way of example only), the preferred EMG configuration is described for Lumbar surgery in Table 1, Thoracolumbar surgery in Table 2, and Cervical surgery in Table 3 below:

Table 1: Lumbar

Color	Channel	Myotome	Nerve	Spinal Level
Red	Right 1	Right Vastus Medialis	Femoral	L2, L3, L4
Orange	Right 2	Right Tibialis Anterior	Common Peroneal	L4, L5
Yellow	Right 3	Right Biceps Femoris	Sciatic	L5, S1, S2
Green	Right 4	Right Medial Gastroc.	Post Tibial	S1, S2
Blue	Left 1	Left Vastus Medialis	Femoral	L2, L3, L4
Violet	Left 2	Left Tibialis Anterior	Common Peroneal	L4, L5
Gray	Left 3	Left Biceps Femoris	Sciatic	L5, S1, S2
White	Left 4	Left Medial Gastroc.	Post Tibial	S1, S2

Table 2: Thoracolumbar

Color	Channel	Myotome	Nerve	Spinal Level
Red	Right 1	Right Abductor Pollicis Brevis	Median	C6, C7, C8, T1
Orange	Right 2	Right Vastus Medialis	Femoral	L2, L3, L4
Yellow	Right 3	Right Tibialis Anterior	Common Peroneal	L4, L5
Green	Right 4	Right Abductor Hallucis	Tibial	L4, L5, S1
Blue	Left 1	Left Abductor Pollicis Brevis	Median	C6, C7, C8, T1
Violet	Left 2	Left Vastus Medialis	Femoral	L2, L3, L4
Gray	Left 3	Left Tibialis Anterior	Common Peroneal	L4, L5
White	Left 4	Left Abductor Hallucis	Tibial	L4, L5, S1

Table 3: Cervical

Color	Channel	Myotome	Nerve	Spinal Level
Red	Right 1	Right Deltoid	Axilliary	C5, C6
Orange	Right 2	Right Flexor Carpi Radialis	Median	C6, C7, C8
Yellow	Right 3	Right Abductor Pollicis Brevis	Median	C6, C7, C8, T1
Green	Right 4	Right Abductor Hallucis	Tibial	L4, L5, S1
Blue	Left 1	Left Deltoid	Axillary	C5, C6
Violet	Left 2	Left Flexor Carpi Radialis	Median	C6, C7, C8

Gray	Left 3	Left Abductor Pollicis Brevis	Median	C6, C7, C8, T1
White	Left 4	Left Abductor Hallucis	Tibial	L4, L5, S1

[0063] The surgical system 40 employs the algorithm described above to automatically control the delivery of stimulation signals upon test initiation. While it may be used with any of a number of the operable functions of system 40, the multi-channel aspect of the hunting algorithm will be described by way of example only during Nerve Retractor and MEP modes, which will be described in greater detail below. Various additional functions of the system 40 have been previously discussed in detail elsewhere and such discussion is not included herein. Details of the Twitch Test, Screw Test (Basic, Difference, Dynamic), Detection, and SSEP modes may be found in the following commonly owned patent applications, each of which is expressly incorporated by reference as if set forth herein in their entireties: Int'l Patent App. No. PCT/US2005/036089, entitled "System and Methods for Assessing the Neuromuscular Pathway Prior to Nerve Testing," filed October 7, 2005; Int'l Patent App. No. PCT/US02/35047 entitled "System and Methods for Performing Percutaneous Pedicle Integrity Assessments," filed on October 30, 2002; Int'l Patent App. No. PCT/US2004/025550, entitled "System and Methods for Performing Dynamic Pedicle Integrity Assessments," filed on August 5, 2004; Int'l Patent App. No PCT/US02/22247, entitled "System and Methods for Determining Nerve Proximity, Direction, and Pathology During Surgery," filed on July 11, 2002; the entire contents of each are hereby incorporated by reference as if set forth fully herein.

[0064] The surgical system 40 accomplishes neural pathology monitoring (via Nerve Retractor Mode, by way of example only) by electrically stimulating a nerve root according to the hunting algorithm, via one or more stimulation electrodes at the distal end of the nerve root retractor 60 or 61 and monitoring each channel for corresponding evoked muscle responses. Threshold hunting continues according to the algorithm until I_{thresh} is determined for each channel in range. A pathology assessment is made by determining a baseline stimulation threshold with direct contact between the nerve retractor 60 or 61 and the nerve, prior to retraction. Subsequent stimulation thresholds are determined during retraction and they are compared to the baseline threshold. An increase in I_{thresh} over time is an indication that the nerve function is deteriorating and retraction should be reduced or stopped altogether to prevent permanent damage. A decrease in I_{thresh} over time may be an indication that nerve function has been at least partially restored.

[0065] I_{thresh} results determined by the algorithm may be displayed to the surgeon on the exemplary screen display of FIG. 12 (to be displayed on display 64 of FIG. 10). Preferably, baseline, directly previous, and current I_{thresh} results are shown for each channel. The display of I_{thresh} values may be accompanied by a color code making use of the colors Red, Yellow, and Green. The color Red may be displayed when the difference between the baseline and actual value is within a predetermined "unsafe" level. The color Green may be displayed when the difference between the baseline I_{thresh} and current I_{thresh} is within a predetermined "safe" level. Yellow may be displayed when difference between the baseline I_{thresh} and current I_{thresh} falls between predetermined unsafe and safe levels.

[0066] The nerve root retractor 60 may be dimensioned in any number of different fashions, such as retractors 60 and 61 illustrated in FIG. 10, including having a generally curved distal region (shown as a side view in FIG. 10 to illustrate the concave region where the nerve will be positioned while retracted), and of sufficient dimension (width and/or length) and rigidity to maintain the retracted nerve in a desired position during surgery. The nerve root retractors 60, 61 may also be equipped with a handle 68 having one or more buttons for selectively initiating the algorithm and applying the electrical stimulation to the stimulation electrode(s) at the distal end of the nerve root retractor 60, 61. In one embodiment, the nerve root retractor 60, 61 is disposable and the handle 68 is reusable and autoclavable.

[0067] The surgical system 40 may perform MEP by electrically stimulating the motor cortex of the brain with electrical stimulation signals which creates an action potential that travels along the spinal cord and into the descending nerves, evoking activity from muscles innervated by the nerves. EMG responses of the muscles are recorded by the system 40 and analyzed in relation to the stimulation signal. Stimulation and analysis are preferably executed according to the multi-channel hunting algorithm described above.

[0068] MEP stimulation signals are generated in the MEP stimulator 21 and delivered to the motor cortex via a pair of stimulation electrodes 54 connected to the MEP stimulator 21 and placed on opposite sides of the cranium. Each MEP signal is preferably delivered as a group or train of multiple pulses, such as that illustrated in FIG. 3. Stimulation signals are delivered at a constant current but MEP stimulator 46 is capable of delivering stimulation signals over a large range of currents in order to execute the hunting algorithm. By way of example only, MEP stimulator 46 may deliver a first stimulation signal at a constant current of 100mA, a second stimulation signal at constant current of 200mA, a third stimulation signal of 400mA, and a fourth stimulation signal of 800mA. Preferably, stimulation signals may be delivered at a current ranging from 0mA to 1000mA. It should be understood of course that the hunting algorithm employed by the system 40 need not be limited to any range. MEP stimulator 46 may deliver either a positive pulse or a negative pulse. Additionally, MEP stimulator 46 may have more than one stimulation channel, thus, additional pairs of stimulation electrodes 54 may be arranged on the skull. This is advantageous in that the effectiveness of a stimulation signal originating from one position on the skull may vary between different recording sites.

[0069] MEP stimulator 46 is communicatively linked to the control unit 42 which commands the stimulator 46 to deliver electrical signals according to predetermined parameters (such as current level, among others) at the proper time. MEP stimulator 46 may be communicatively linked to the control unit 40 via any suitable connection such as a data cable or wireless technology, etc... The MEP stimulator 46 may be positioned outside the sterile area but should be located such that the stimulation electrodes 54, attached to the stimulator 46, may be positioned on the patient's head without tension. By way of example, MEP stimulator 46 may be placed on the surgical table adjacent to the patient's head. Optionally, the MEP stimulator 46 may be fashioned with a mount or hook (not shown) and hung from an IV pole near the patient's head.

[0070] The multi-channel threshold hunting algorithm described above is utilized to determine a baseline I_{thresh} for each channel, preferably prior to or in the early stages of a surgical procedure. It should be appreciated, however, that a new baseline I_{thresh} may be determined at any time during the procedure at the option of the surgeon or other qualified operator. Having determined a baseline I_{thresh} for each channel, subsequent monitoring may be performed as desired throughout the procedure and recovery period to obtain updated I_{thresh} values for each channel. Each new determination of I_{thresh} is compared by the surgical system 40 to the baseline I_{thresh} for the appropriate channel. The difference (ΔI_{thresh}) between the baseline I_{thresh} and the new I_{thresh} is calculated by the system 40 and the ΔI_{thresh} value is compared to predetermined "safe" and "unsafe" values. If ΔI_{thresh} is greater than the predetermined safe level, the user is alerted to a potential complication and action may be taken to avoid or mitigate the problem. The speed with which the multi-channel MEP threshold hunting algorithm is able to determine I_{thresh} across all channels, and the simplicity with which the data communicated to the user may be interpreted, allows the user to increase the frequency of MEP monitoring conducted during a procedure without a concurrent increase in overall surgery time. This provides significant benefit to the patient by reducing the time intervals in between MEP monitoring episodes during which an injury to the spinal cord may go undetected.

[0071] The display of I_{thresh}, shown by way of example only in the exemplary MEP screen display of FIG. 13 (to be displayed on display 64 of FIG. 10), may be accompanied by a color code so that the operator may quickly easily comprehend the situation and avoid neurological impairment to the patient (e.g. red for "danger," yellow for "caution" and green for "safe"). The color Red may be displayed when the difference between the baseline and actual value, ΔI_{thresh}, is within a predetermined "unsafe" level. The color Green may be displayed when the ΔI_{thresh} is within a predetermined "safe" level. Yellow may be displayed when the ΔI_{thresh} value falls between predetermined unsafe and safe levels.

[0072] It will be readily appreciated that various modifications may be undertaken, or certain steps or algorithms omitted or substituted, without departing from the scope of the present invention. By way of example only, although the multi-channel hunting algorithm is discussed herein in terms of finding I_{thresh} (the lowest stimulation current that evokes a significant EMG response), it is contemplated that alternative stimulation thresholds may be determined by the hunting algorithm. By way of example only, the hunting algorithm may be employed to determine a stimulation voltage threshold, $Vstim_{thresh}$. This is the lowest stimulation voltage (as opposed to the lowest stimulation current) necessary to evoke a significant EMG response,

V_{thresh}. The bracketing and bisection states are conducted, omitting stimulations and conducting confirmation step when applicable, as described above., with brackets based on voltage being substituted for the current based brackets previously described. By way of further example, although use of the multi-channel hunting algorithm was described with reference to a nerve retractor and MEP monitoring, it will be appreciated that the algorithm may be employed for a variety or neurophysiology functions including, but not necessarily limited to, pedicle integrity testing, nerve proximity monitoring, and nerve direction monitoring.

[0073] Moreover, although use of the algorithm was illustrated with reference to the surgical system 40, it will be appreciated as within the scope of the invention to use the multi-channel hunting algorithm as described herein with any number of different neurophysiology based testing systems.

[0074] While this invention has been described in terms of a best mode for achieving this invention's objectives, it will be appreciated by those skilled in the art that variations may be accomplished in view of these teachings without deviating from the spirit or scope of the present invention. For example, the present invention may be implemented using any combination of computer programming software, firmware or hardware. As a preparatory step to practicing the invention or constructing an apparatus according to the invention, the computer programming code (whether software or firmware) according to the invention will typically be stored in one or more machine readable storage mediums such as fixed (hard) drives, diskettes, optical disks, magnetic tape, semiconductor memories such as ROMs, PROMs, etc., thereby making an article of manufacture in accordance with the invention. The article of manufacture containing the computer programming code is used by either executing the code directly from the storage device, by copying the code from the storage device into another storage device such as a hard disk, RAM, etc. or by transmitting the code on a network for remote execution. As can be envisioned by one of skill in the art, many different combinations of the above may be used and accordingly the present invention is not limited by the specified scope.

What is claimed is:

1. A method for performing neurophysiologic assessments, comprising:
delivering a plurality of electrical stimulation signals near tissue;
detecting neuromuscular responses evoked by said signals; and
omitting stimulation signals when said neuromuscular response is predictable.

2. The method of claim 1, wherein said plurality of stimulation signals are each defined by a selected current level.

3. The method of claim 2, wherein at least one of pedicle integrity, nerve proximity, nerve pathology, and spinal cord health may be determined based upon an identified relationship between said current levels and said neuromuscular responses.

4. The method of claim 3, wherein said identified relationship is the threshold current level required to evoke a neuromuscular response of a predetermined magnitude.

5. The method of claim 4, wherein said neuromuscular response is detected by an EMG sensor and said magnitude is measured as a peak-to-peak voltage.

6. The method of claim 5, wherein said predetermined magnitude is a peak-to-peak voltage from within the range of 20uV to 100uV.

7. The method of claim 5, wherein at least two sensors are deployed to monitor the neuromuscular response of different myotomes, said at least two sensors corresponding to different monitoring channels, and wherein a threshold current level is determined for each channel.

8. The method of claim 7, wherein a threshold current level is found for between 2 to 8 channels.

9. The method of claim 7, wherein determining the threshold current for each channel comprises establishing for each channel a bracket within which the threshold current must lie.

10. The method of claim 7, wherein determining the threshold current for each channel comprises bisecting to a predetermined range a bracket established on each channel.

11. The method of claim 7, wherein an algorithm is executed to determine the threshold current for each channel.

12. The method of claim 11, wherein said algorithm is biased to find the threshold current on the channel with the lowest threshold first and find the threshold current on the channel with the highest threshold first.

13. The method of claim 11, wherein said algorithm operates by assigning a channel specific status to each selected stimulation current, said status being one of a first status and a second status, said first status applying to a current level which evokes a neuromuscular response one of equal to and greater than said predetermined magnitude and said second status applying to a current level which evokes a neuromuscular response less than said predetermined magnitude.

14. The method of claim 13, wherein said algorithm determines said status of a selected stimulation current by at least one of stimulating at said selected current and measuring the magnitude of the neuromuscular response, and inferring the status based on previously captured data.

15. The method of claim 14, wherein said previously captured data includes the neuromuscular response measured on one channel in relation to a stimulation current delivered to determine the threshold current on another channel.

16. The method of claim 13, wherein said first status is assigned without directing a stimulation at said selected current if said selected current is one of equal to and greater than a current level previously assigned said first status on the applicable channel.

17. The method of claim 13, wherein said second status is assigned without directing a stimulation signal at said selected current if said selected current is less than a current level previously assigned said second status on the applicable channel.

18. The method of claim 13, wherein said algorithm is based on successive approximation.

19. The method of claim 13, wherein said algorithm comprises a first step of establishing a bracket within which the threshold current must lie and a second step of bisecting the bracket to a predetermined width.

20. The method of claim 19, wherein said bracketing step is carried out for each channel before the algorithm transitions to said bisection step.

21. The method of claim 19, wherein said first step of establishing a bracket and said second step of bisecting the bracket are completed on one channel before beginning the steps again on another channel.

22. The method of claim 19, wherein said first bracket is determined by assigning on each channel one of said first status and said second status to a series of successively doubling stimulation currents, wherein an upper boundary of said first bracket comprises the first stimulation current assigned said first status and a lower boundary of said first bracket comprises the last stimulation current assigned said second status.

23. The method claim 22, wherein said first bracket is bisected on each channel by assigning one of said first status and said second status to a stimulation current level at the midpoint of said first bracket, said midpoint forming a second bracket with one of said upper boundary and said lower boundary of said first bracket, said midpoint forming a lower boundary of said second

bracket when said midpoint is assigned said first status and said midpoint forming an upper boundary of said second bracket when said midpoint is assigned said second status.

24. The method of claim 4, wherein said threshold current level is determined for each of at least two channels.

25. The method of claim 24, wherein the current of said stimulation signals is automatically adjusted in a first sequence to establish a bracket which contains the stimulation threshold on a first channel.

26. The method of claim 25, wherein the current of said stimulation signals is automatically adjusted in a second sequence to establish a bracket which contains the stimulation threshold on a second channel, wherein at least one of said stimulation currents in said second sequence equals one of said stimulation currents in said first sequence, and said stimulation current is omitted from said second sequence.

27. The method of claim 4, wherein delivery of said stimulation signals is directed from a control unit, said control unit communicating with a stimulation source and a sensor configured to detect the neuromuscular responses.

28. The method of claim 27, comprising the additional step of displaying on a display linked to said control unit at least one of alpha-numeric, graphic, and color based indica to communicate the stimulation threshold results.

29. The method of claim 28, wherein said display includes a graphical user interface and comprising the further step of imputing user instructions including one or more of starting stimulation, stopping stimulation, selecting a function, and adjusting system parameters.

30. The method of claim 27, wherein the stimulation source is an MEP stimulator and wherein the stimulation signals are delivered to the motor cortex.

31. The method of claim 30, comprising the further step of determining the threshold current at least twice during a surgical procedure and comparing the later threshold current to the earlier threshold current to indicate the health of the spinal cord.

32. The method of claim 27, comprising the further step of retracting a nerve out of a surgical corridor using a nerve retractor electrically coupled to said stimulation source.

33. The method of claim 32, comprising the further step of determining the threshold current at least twice while the nerve is retracted and comparing the later threshold current to the earlier threshold current to indicate the pathology of the nerve.

34. A software application operated on a neurophysiology monitoring system, said software application configured to (a) command delivery of a plurality of stimulation signals at selected current amplitudes, (b) receive and process neuromuscular response data evoked by stimulation at said currents, (c) establish for each selected current amplitude one of a first status and a second status based on the magnitude of the corresponding neuromuscular response, and (d) omit delivery of a stimulation signal of at least one selected current when the status of said at least one current is predictable.

35. The software application of claim 34, wherein at least one of pedicle integrity, nerve proximity, nerve pathology, and spinal cord health is assessed based upon an identified relationship between said current amplitudes and said neuromuscular responses.

36. The software application of claim 35, wherein said identified relationship is the threshold amplitude necessary to evoke a neuromuscular response of a predetermined magnitude.

37. The software application of claim 36, wherein said software application receives neuromuscular response data over at least two channels corresponding to an equal number of sensors deployed to monitor neuromuscular responses of different myotomes.

38. The software application of claim 37, wherein said threshold current is determined for each of the at least two channels.

39. The software application of claim 38, wherein there are 8 channels relaying neuromuscular response data said threshold current is determined for all 8 channels.

40. The software application of claim 36, wherein said first status applies to a current level which evokes a neuromuscular response one of equal to and greater than said predetermined magnitude and said second status applies to a current level which evokes a neuromuscular response less than said predetermined magnitude.

41. The software application of claim 34, wherein said software application access a memory on said neurophysiology monitoring system and retrieves data corresponding to neuromuscular responses associated with previous stimulations.

42. The software application of claim 41, wherein the data retrieved is used by the software application to infer one of said first status and said second status to a given stimulation current and omit delivery of that stimulation current.

43. The software application of claim 38, wherein said software application executes an algorithm to determine said threshold current for each of the at least two channels.

44. The software application of claim 43, wherein said algorithm is based on successive approximation.

45. The software application of claim 43, wherein said algorithm comprises a first step of establishing a bracket within which the threshold current must lie and a second step of bisecting the bracket to a predetermined width.

46. The software application of claim 43, wherein said bracketing step is carried out for each channel before the algorithm transitions to said bisection step.

47. The software application of claim 43, wherein said first step of establishing a bracket and said second step of bisecting the bracket are completed on one channel before beginning the steps again on another channel.

48. The software application of claim 41, wherein said software application determines said status of a selected stimulation current by at least one of directing stimulation at said selected current and measuring the magnitude of the neuromuscular response, and inferring the status based on the neuromuscular response data from previous stimulations.

49. The software application of claim 48, wherein said previous neuromuscular response data includes neuromuscular responses measured on one channel in relation to a stimulation current delivered to determine the threshold current on another channel.

50. The software application claim 34, wherein said first status is assigned without directing a stimulation at said selected current if said selected current is one of equal to and greater than a current level previously assigned said first status on the applicable channel.

51. The software application claim 34, wherein said second status is assigned without directing a stimulation signal at said selected current if said selected current is less than a current level previously assigned said second status on the applicable channel.

52. The software application of claim 36, wherein said software application is further configured to direct the display of at least one of alpha-numeric, graphic, and color based indica to communicate the stimulation threshold results.

53. The software application of claim 36, wherein said software application is further configured to receive user instructions from a graphical user interface including one or more of starting stimulation, stopping stimulation, selecting a function, and adjusting system parameter

54. An algorithm for directing the delivery of stimulation signals to determine the stimulation threshold of neural tissue relative to at least two EMG monitoring channels, comprising the steps of:

(a) determining a first stimulation threshold on a first channel;

(b) establishing for a second channel a bracket within which a second stimulation threshold must lie;

(c) bisecting the bracket to a predetermined range and selecting any value within the predetermined range as the second stimulation threshold; and

(d) omitting the delivery of at least one stimulation signal during at least one of step (b) and step (c) when the EMG response to a selected stimulation current is predictable.

55. The algorithm of claim 54, wherein the step (b) of establishing a bracket for the second channel comprises the further steps of selecting a series of stimulation currents and determining an EMG result for each current.

56. The algorithm of claim 55, wherein the step of determining an EMG result is accomplished via one of stimulating at the selected current while monitoring the EMG response, and examining previously obtained EMG responses to infer the likely result.

57. The algorithm of claim 56, wherein the series of stimulation currents begins at a predetermined minimum current and exponentially doubles thereafter until an EMG result of a predetermined magnitude is evoked, the first simulation current determined to evoke the predetermined magnitude response forms an upper boundary of the bracket and the last stimulation current determined to not evoke the predetermined magnitude response forms a lower boundary of the bracket.

58. The algorithm of claim 57, wherein the step (c) of bisecting the bracket formed in step (b) comprises the further step of determining an EMG result for a stimulation current at the midpoint of the bracket and shrinking the bracket to one of an upper half and a lower half based upon the EMG result at the midpoint and then repeating the step until a bracket of a predetermined range is formed, the second stimulation threshold being selected as any value within the final bracket.

59. The algorithm of claim 58, wherein the step of determining an EMG result for the midpoint current is accomplished via one of stimulating at the midpoint current while monitoring the EMG response, and examining previously obtained EMG responses to infer the likely result.

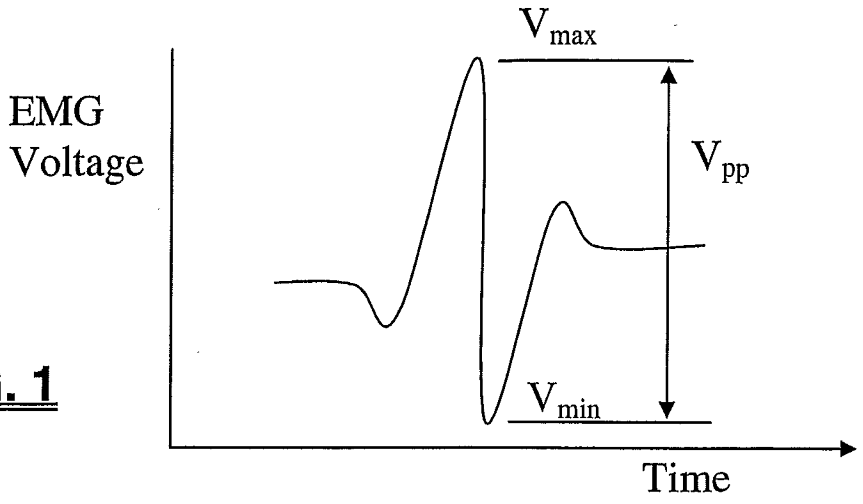


FIG. 1

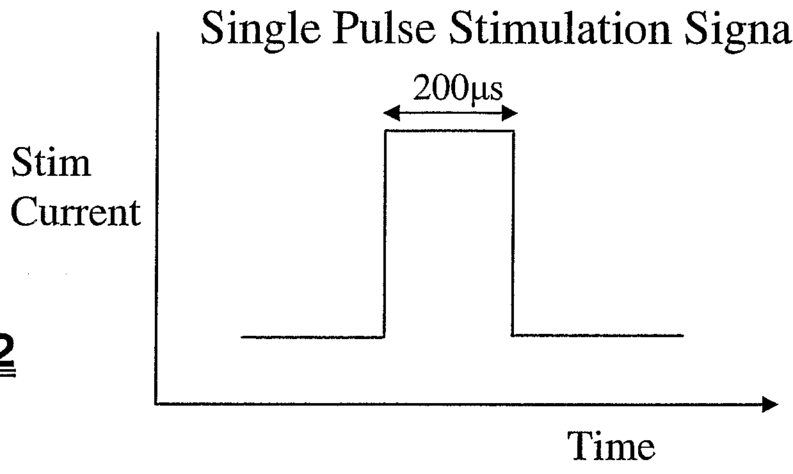


FIG. 2

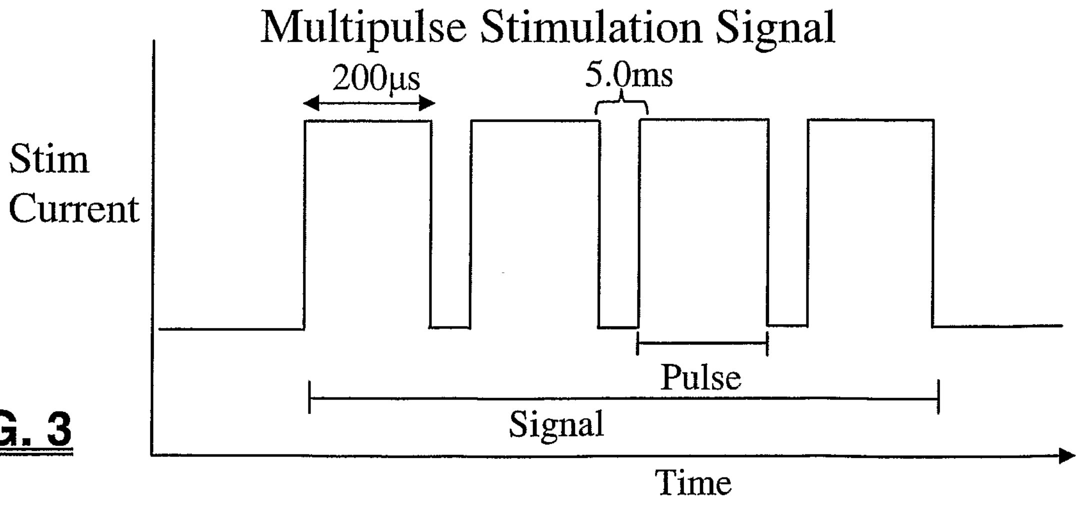


FIG. 3

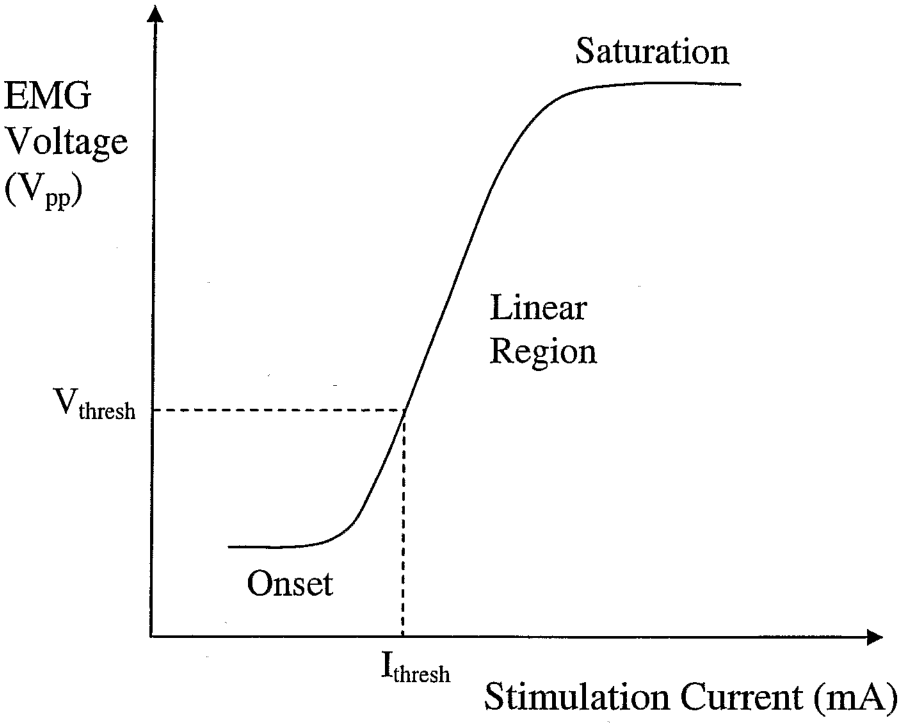

EMG
Voltage
(V_{pp})
Saturation
Linear
Region
V_{thresh}
Onset
I_{thresh}
Stimulation Current (mA)

FIG. 4

FIG. 5A

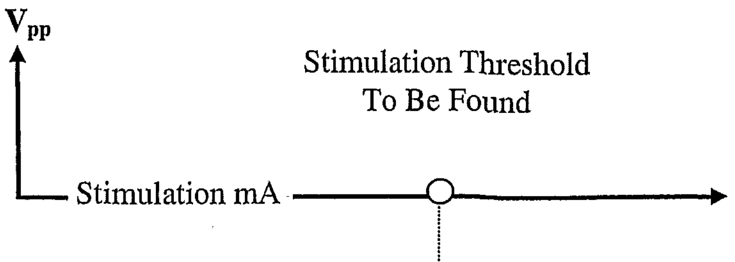


FIG. 5B

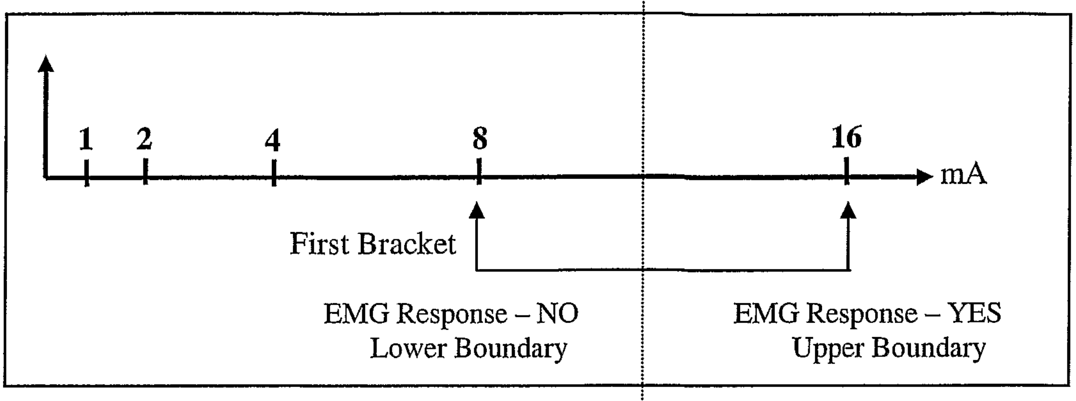


FIG. 5C

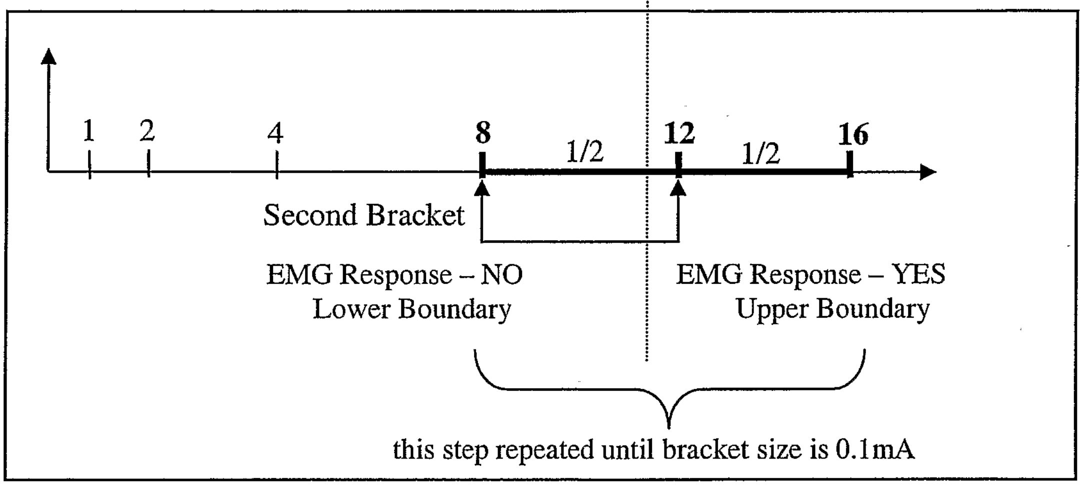
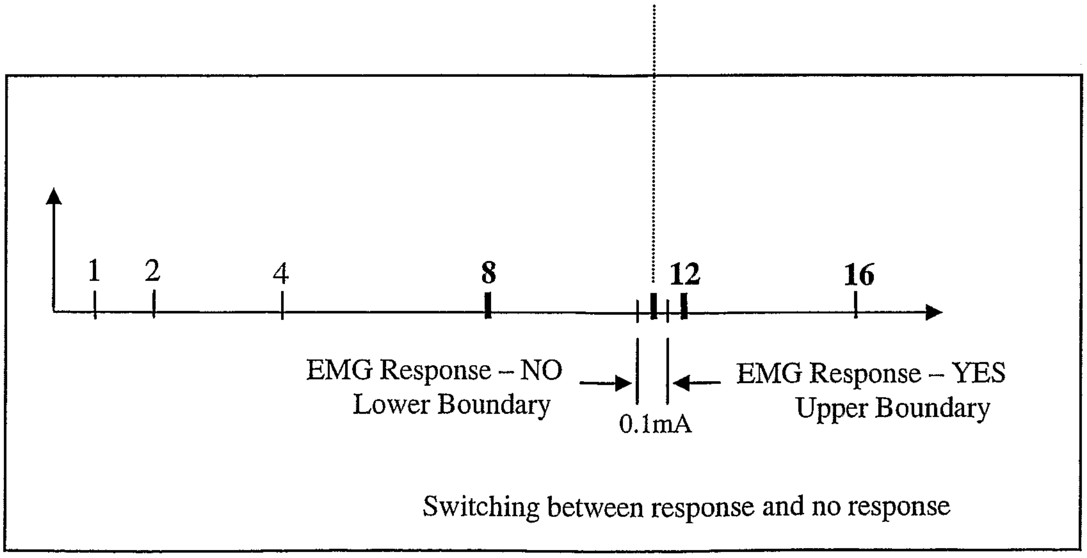


FIG. 5D



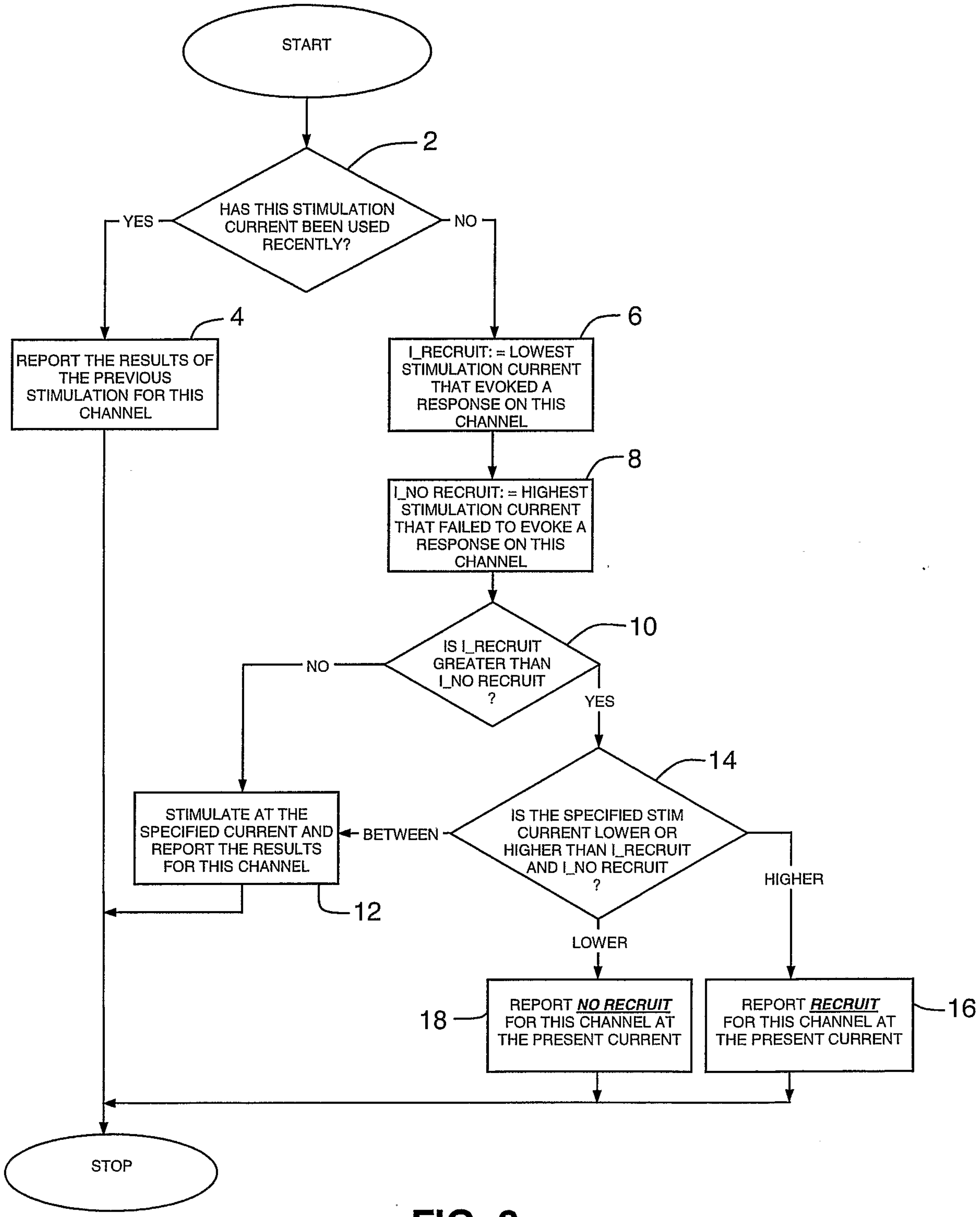

START
2
HAS THIS STIMULATION CURRENT BEEN USED RECENTLY?
YES
NO
4
REPORT THE RESULTS OF THE PREVIOUS STIMULATION FOR THIS CHANNEL
6
I_RECRUIT: = LOWEST STIMULATION CURRENT THAT EVOKED A RESPONSE ON THIS CHANNEL
8
I_NO RECRUIT: = HIGHEST STIMULATION CURRENT THAT FAILED TO EVOKE A RESPONSE ON THIS CHANNEL
10
IS I_RECRUIT GREATER THAN I_NO RECRUIT ?
NO
YES
14
IS THE SPECIFIED STIM CURRENT LOWER OR HIGHER THAN I_RECRUIT AND I_NO RECRUIT ?
BETWEEN
HIGHER
LOWER
STIMULATE AT THE SPECIFIED CURRENT AND REPORT THE RESULTS FOR THIS CHANNEL
12
18
REPORT NO RECRUIT FOR THIS CHANNEL AT THE PRESENT CURRENT
REPORT RECRUIT FOR THIS CHANNEL AT THE PRESENT CURRENT
16
STOP

FIG. 6

FIG. 7A

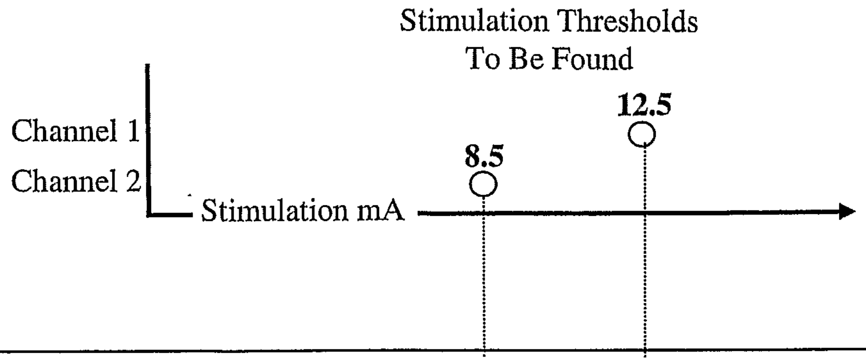


FIG. 7B

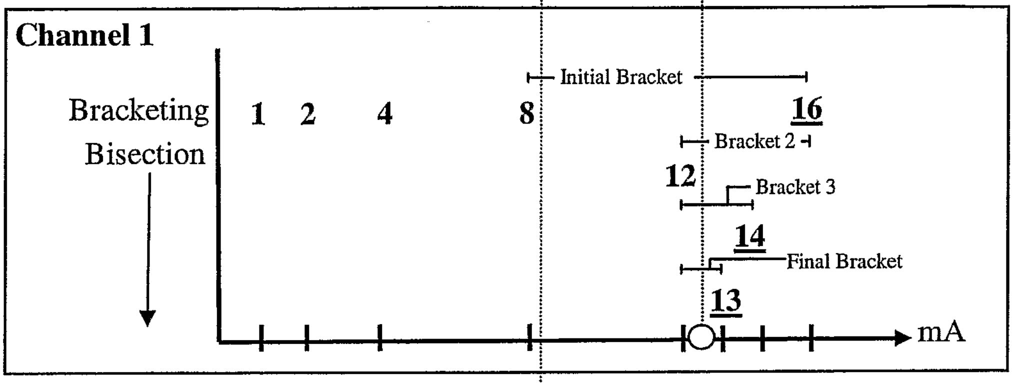
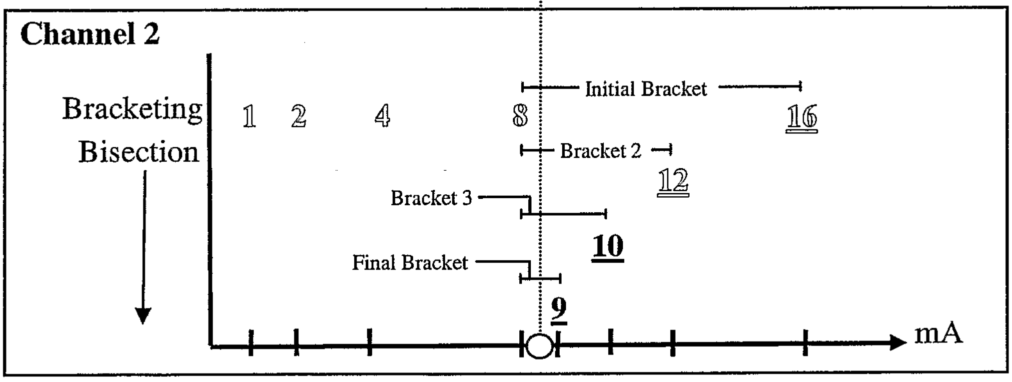


FIG. 7C



LEGEND

= actual recruit

= inferred recruit

= actual nonrecruit

= inferred nonrecruit

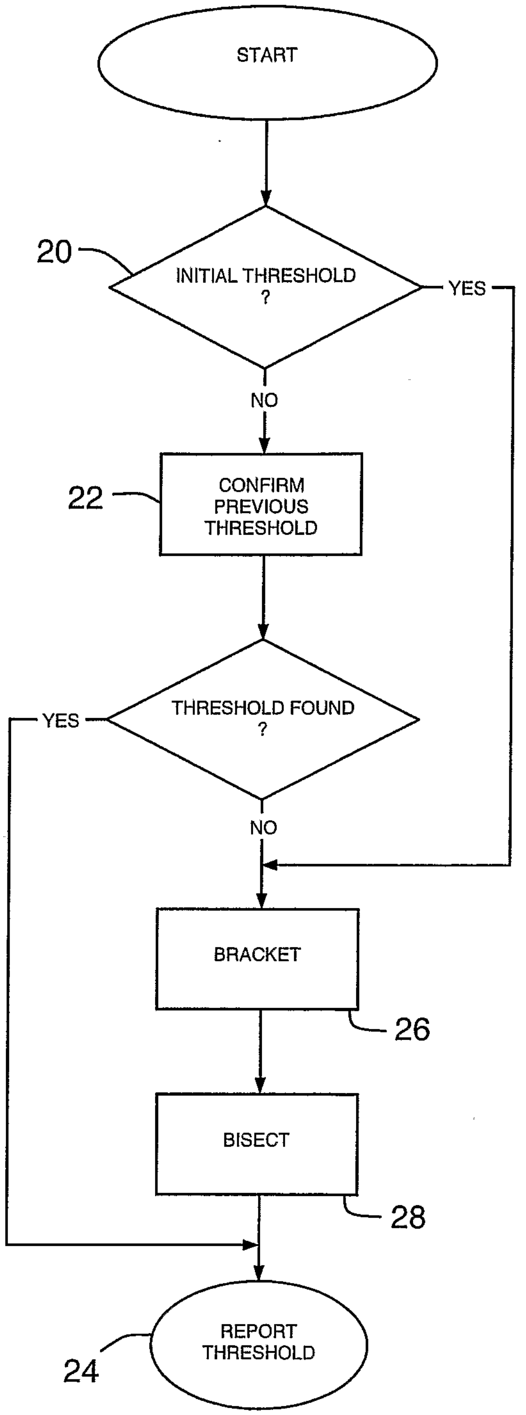

START
20
INITIAL THRESHOLD ?
YES
NO
22
CONFIRM PREVIOUS THRESHOLD
THRESHOLD FOUND ?
YES
NO
BRACKET
26
BISECT
28
REPORT THRESHOLD
24

FIG. 8

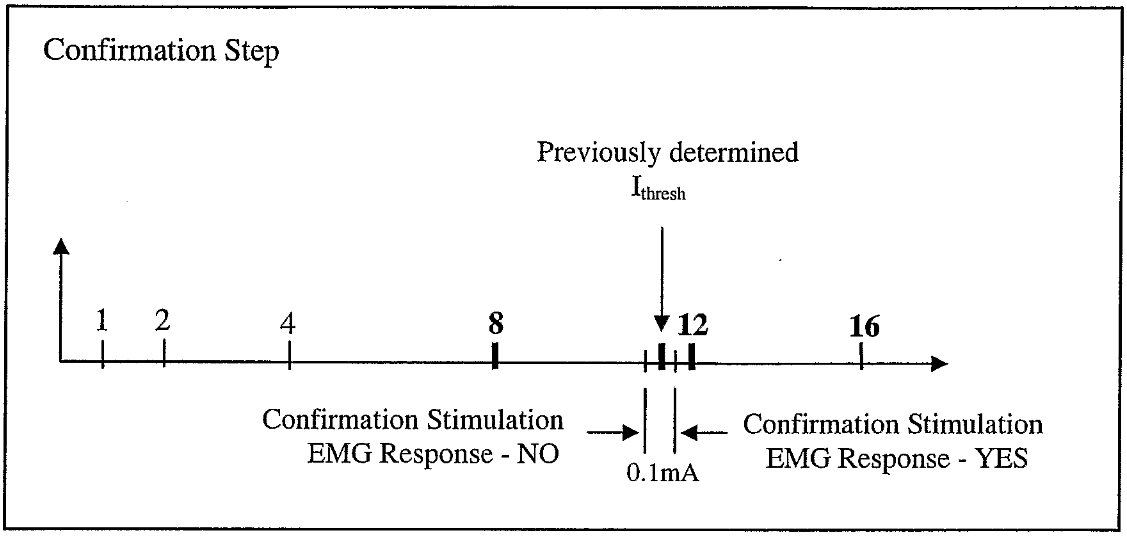

Confirmation Step
Previously determined
I_{thresh}
1
2
4
8
12
16
Confirmation Stimulation
EMG Response - NO
0.1mA
Confirmation Stimulation
EMG Response - YES

FIG. 9

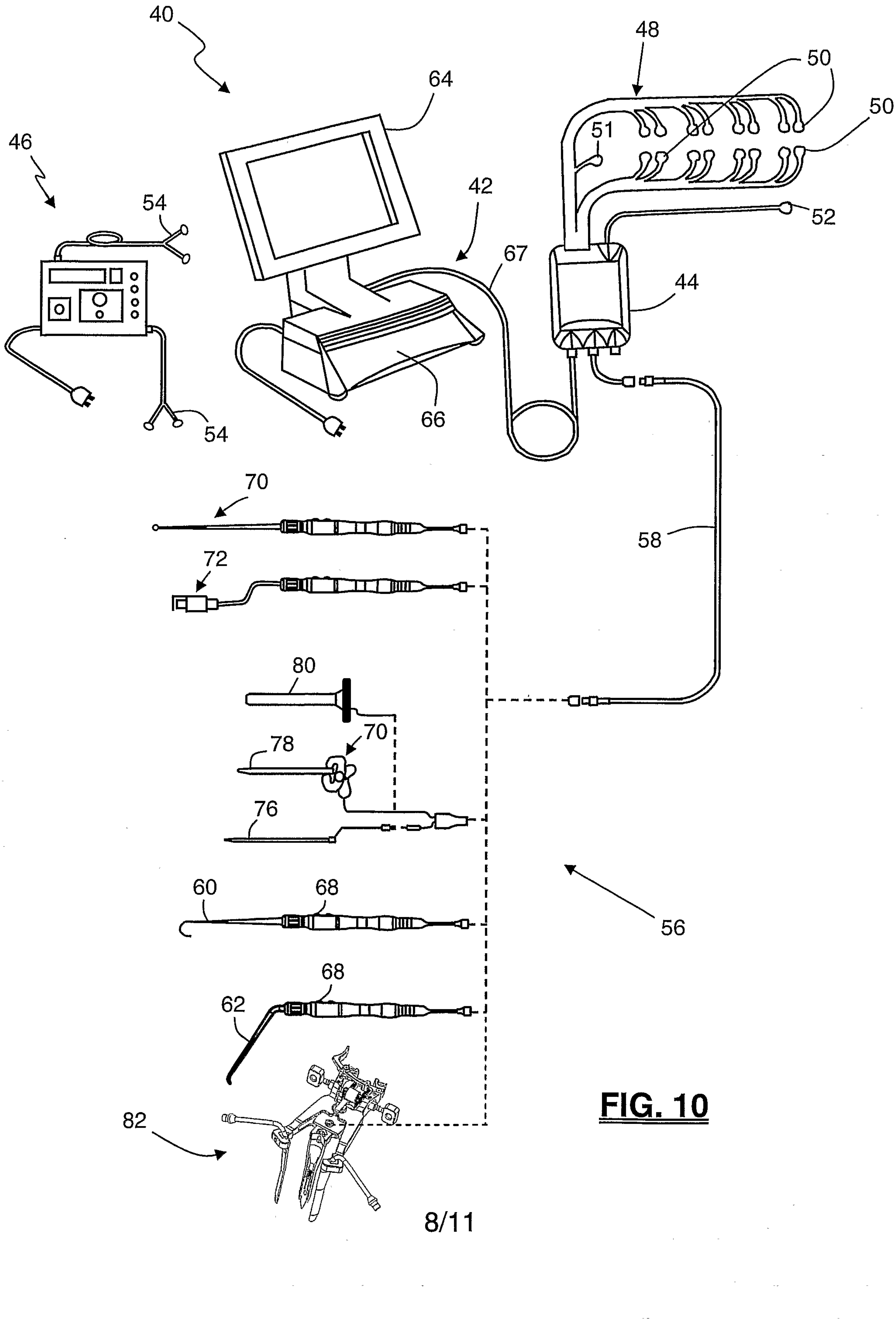

40
46
54
54
64
42
67
66
48
50
50
51
52
44
58
70
72
80
70
78
76
60
68
56
68
62
82

FIG. 10

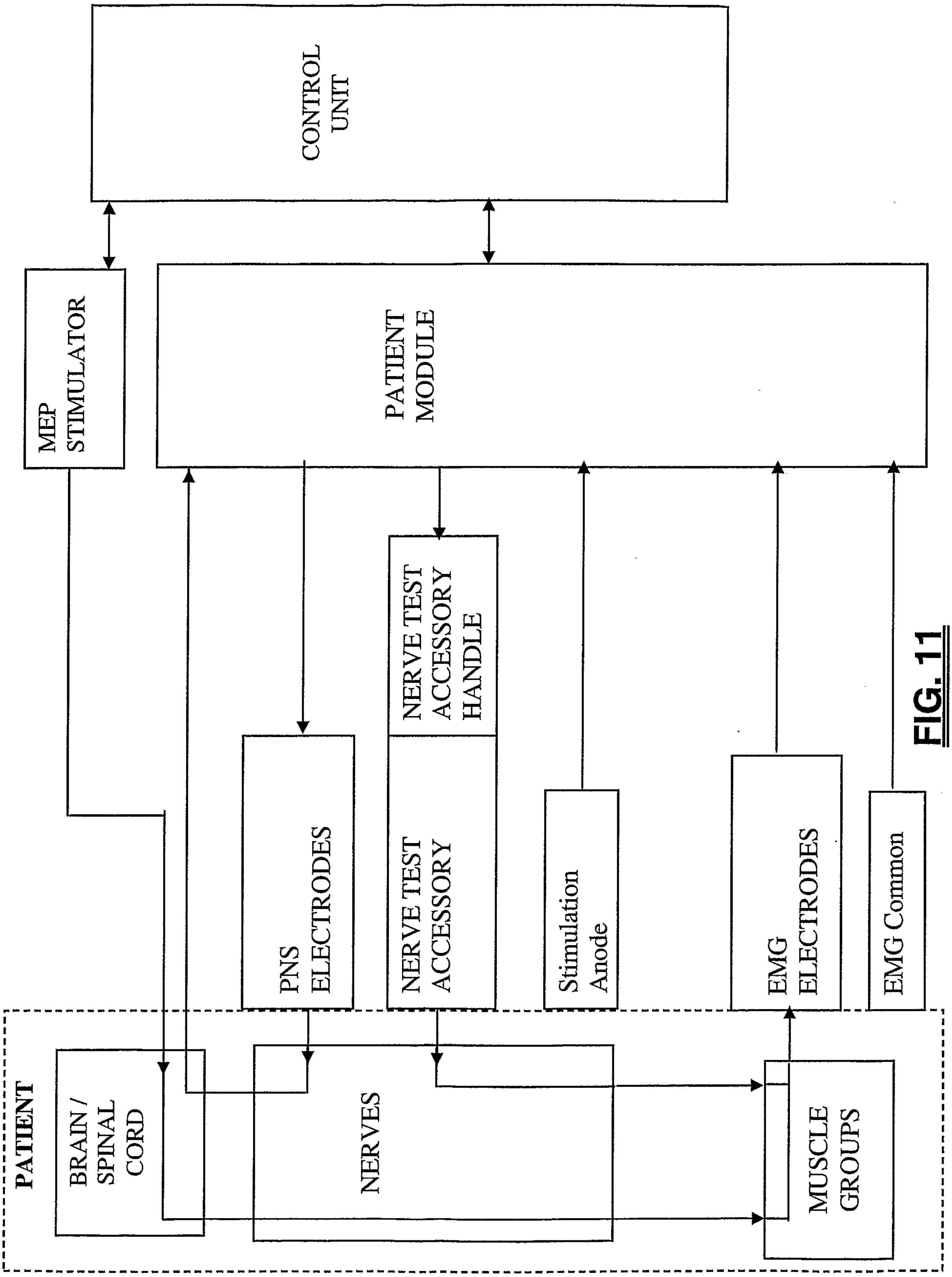
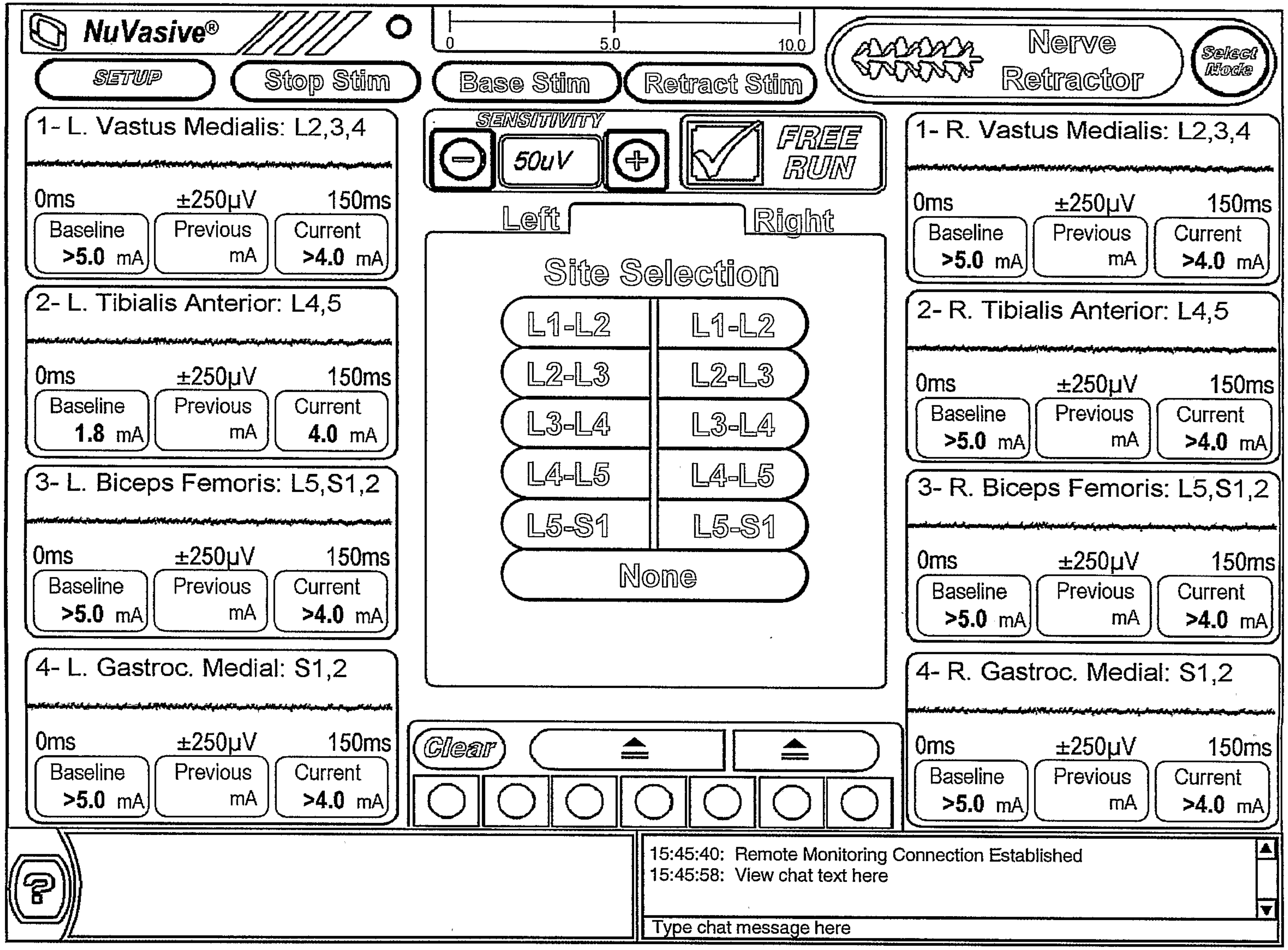

CONTROL UNIT
MEP STIMULATOR
PATIENT MODULE
PNS ELECTRODES
NERVE TEST ACCESSORY HANDLE
NERVE TEST ACCESSORY
Stimulation Anode
EMG ELECTRODES
EMG Common
PATIENT
BRAIN / SPINAL CORD
NERVES
MUSCLE GROUPS

FIG. 11



1- L. Vastus Medialis: L2,3,4
0ms ±250µV 150ms
Baseline >5.0 mA
Previous mA
Current >4.0 mA

2- L. Tibialis Anterior: L4,5
0ms ±250µV 150ms
Baseline 1.8 mA
Previous mA
Current 4.0 mA

3- L. Biceps Femoris: L5,S1,2
0ms ±250µV 150ms
Baseline >5.0 mA
Previous mA
Current >4.0 mA

4- L. Gastroc. Medial: S1,2
0ms ±250µV 150ms
Baseline >5.0 mA
Previous mA
Current >4.0 mA

1- R. Vastus Medialis: L2,3,4
0ms ±250µV 150ms
Baseline >5.0 mA
Previous mA
Current >4.0 mA

2- R. Tibialis Anterior: L4,5
0ms ±250µV 150ms
Baseline >5.0 mA
Previous mA
Current >4.0 mA

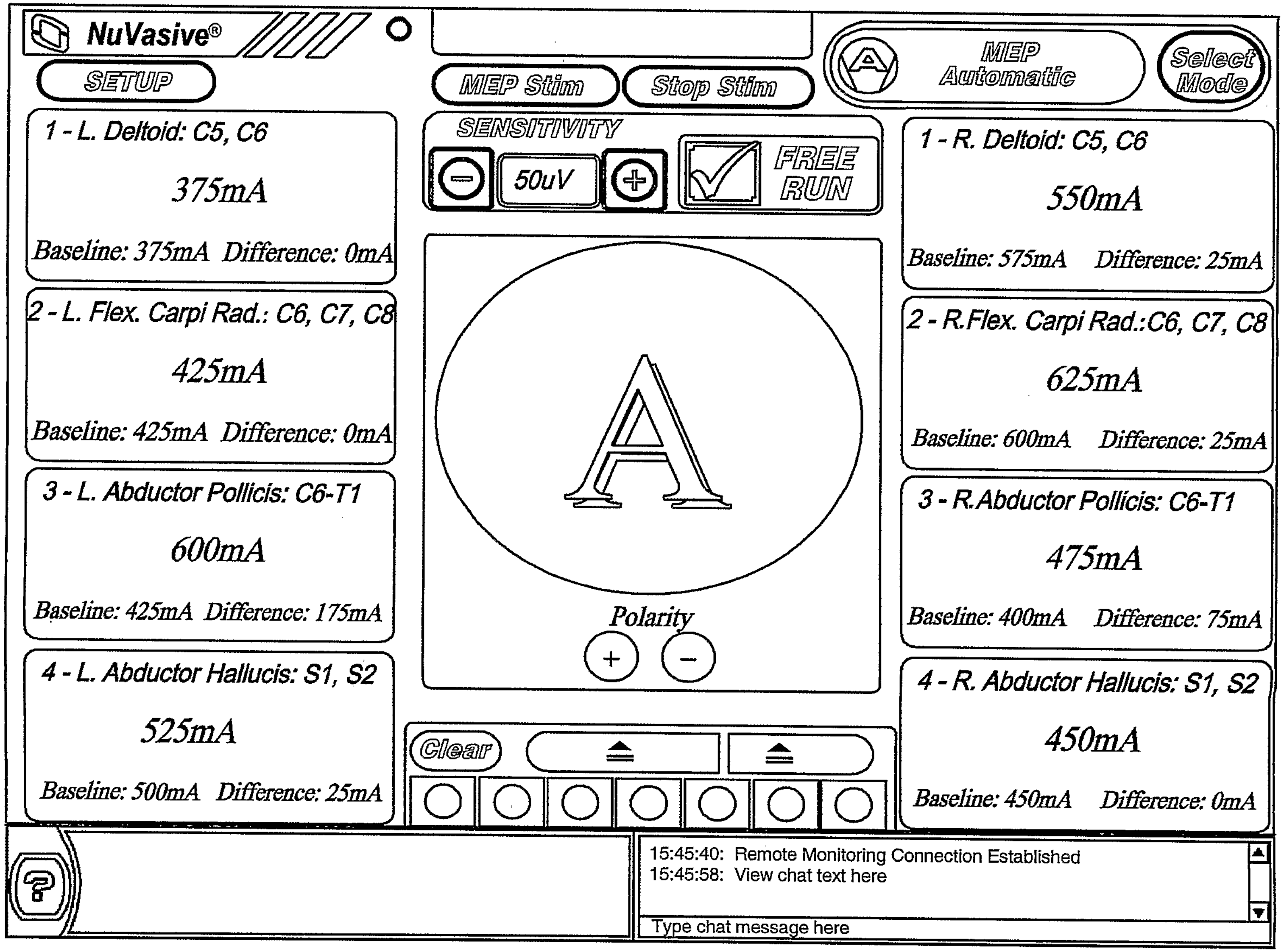
3- R. Biceps Femoris: L5,S1,2
0ms ±250µV 150ms
Baseline >5.0 mA
Previous mA
Current >4.0 mA

4- R. Gastroc. Medial: S1,2
0ms ±250µV 150ms
Baseline >5.0 mA
Previous mA
Current >4.0 mA

15:45:40: Remote Monitoring Connection Established
15:45:58: View chat text here

Type chat message here

FIG. 12



1 - L. Deltoid: C5, C6
375mA
Baseline: 375mA Difference: 0mA

2 - L. Flex. Carpi Rad.: C6, C7, C8
425mA
Baseline: 425mA Difference: 0mA

3 - L. Abductor Pollicis: C6-T1
600mA
Baseline: 425mA Difference: 175mA

4 - L. Abductor Hallucis: S1, S2
525mA
Baseline: 500mA Difference: 25mA

1 - R. Deltoid: C5, C6
550mA
Baseline: 575mA Difference: 25mA

2 - R.Flex. Carpi Rad.:C6, C7, C8
625mA
Baseline: 600mA Difference: 25mA

3 - R.Abductor Pollicis: C6-T1
475mA
Baseline: 400mA Difference: 75mA

4 - R. Abductor Hallucis: S1, S2
450mA
Baseline: 450mA Difference: 0mA

15:45:40: Remote Monitoring Connection Established
15:45:58: View chat text here

Type chat message here

FIG. 13