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(73) Patenthaver: **Saluda Medical Pty Limited, Level 1 , 407 Pacific Highway, Artarmon, NSW 2064, Australien**

(72) Opfinder: **PARKER, John Louis, Level 5 13 Garden St, Eveleigh, NSW 2015, Australien**
LAIRD, James Hamilton, Level 5 13 Garden St, Eveleigh, NSW 2015, Australien

(74) Fuldmægtig i Danmark: **Novagraaf Brevets, Bâtiment O2, 2 rue Sarah Bernhardt CS90017, F-92665 Asnières-sur-Seine cedex, Frankrig**

(54) Benævnelse: **APPARAT TIL PÅFØRING AF EN NEURAL STIMULUS**

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DESCRIPTION

Technical Field

[0001] The present invention relates to application of a neural stimulus, and in particular relates to applying a neural stimulus in a controlled manner by using electrodes implanted proximal to the neural pathway.

Background of the Invention

[0002] There are a range of situations in which it is desirable to apply neural stimuli in order to give rise to a compound action potential (CAP). For example, neuromodulation is used to treat a variety of disorders including chronic pain, Parkinson's disease, and migraine. A neuromodulation system applies an electrical pulse to tissue in order to generate a therapeutic effect. When used to relieve chronic pain, the electrical pulse is applied to the dorsal column (DC) of the spinal cord. Such a system typically comprises an implanted electrical pulse generator, and a power source such as a battery that may be rechargeable by transcutaneous inductive transfer. An electrode array is connected to the pulse generator, and is positioned in the dorsal epidural space above the dorsal column. An electrical pulse applied to the dorsal column by an electrode causes the depolarisation of neurons, and generation of propagating action potentials. The fibres being stimulated in this way inhibit the transmission of pain from that segment in the spinal cord to the brain. To sustain the pain relief effects, stimuli are applied substantially continuously, for example at 100 Hz.

[0003] While the clinical effect of spinal cord stimulation (SCS) is well established, the precise mechanisms involved are poorly understood. The DC is the target of the electrical stimulation, as it contains the afferent Aβ fibres of interest. Aβ fibres mediate sensations of touch, vibration and pressure from the skin, and are thickly myelinated mechanoreceptors that respond to non-noxious stimuli. The prevailing view is that SCS stimulates only a small number of Aβ fibres in the DC. The pain relief mechanisms of SCS are thought to include evoked antidromic activity of Aβ fibres having an inhibitory effect, and evoked orthodromic activity of Aβ fibres playing a role in pain suppression. It is also thought that SCS recruits Aβ nerve fibres primarily in the DC, with antidromic propagation of the evoked response from the DC into the dorsal horn thought to synapse to wide dynamic range neurons in an inhibitory manner.

[0004] Neuromodulation may also be used to stimulate efferent fibres, for example to induce motor functions. In general, the electrical stimulus generated in a neuromodulation system triggers a neural action potential which then has either an inhibitory or excitatory effect. Inhibitory effects can be used to modulate an undesired process such as the transmission of pain, or to cause a desired effect such as the contraction of a muscle.

[0005] The action potentials generated among a large number of fibres sum to form a compound action potential (CAP). The CAP is the sum of responses from a large number of single fibre action potentials. The CAP recorded is the result of a large number of different fibres depolarising. The propagation velocity is determined largely by the fibre diameter and for large myelinated fibres as found in the dorsal root entry zone (DREZ) and nearby dorsal column the velocity can be over 60 ms^{-1}. The CAP generated from the firing of a group of similar fibres is measured as a positive peak potential P1, then a negative peak N1, followed by a second positive peak P2. This is caused by the region of activation passing the recording electrode as the action potentials propagate along the individual fibres. An observed CAP signal will typically have a maximum amplitude in the range of microvolts, whereas a stimulus applied to evoke the CAP is typically several volts.

[0006] For effective and comfortable operation, it is necessary to maintain stimuli amplitude or delivered charge above a recruitment threshold, below which a stimulus will fail to recruit any neural response. It is also necessary to apply stimuli which are below a comfort threshold, above which uncomfortable or painful percepts arise due to increasing recruitment of Aδ fibres which are thinly myelinated sensory nerve fibres associated with acute pain, cold and pressure sensation. In almost all neuromodulation applications, a single class of fibre response is desired, but the stimulus waveforms employed can recruit other classes of fibres which cause unwanted side effects, such as muscle contraction if motor fibres are recruited. The task of maintaining appropriate neural recruitment is made more difficult by electrode migration and/or postural changes of the implant recipient, either of which can significantly alter the neural recruitment arising from a given stimulus, depending on whether the stimulus is applied before or after the change in electrode position or user posture. Postural changes alone can cause a comfortable and effective stimulus regime to become either ineffectual or painful.

[0007] EP 2 243 510 discloses a device for selective high frequency spinal cord modulation for inhibiting pain with reduced side effects (paraesthesia). By using a frequency higher than the refractory period of the target neurons an asynchronous response is evoked.

[0008] MAHNAN, A ET AL.: "Measurement of the current-distance relationship using a novel refractory interaction technique", J. NEURAL ENG., vol. 6, no. 3, 20 May 2009 (2009-05-20), page 036005, discloses sequential stimulation to two spatially separate electrodes and observing the response in order to determine the relationship between the threshold current and the electrode to fibre distance.

[0009] Throughout this specification the word "comprise", or variations such as "comprises" or "comprising", will be understood to imply the inclusion of a stated element, integer or step, or group of elements, integers or steps, but not the exclusion of any other element, integer or step, or group of elements, integers or steps.

Summary of the Invention

[0010] The present invention provides a device for applying a neural stimulus, according to claim 1. Preferred embodiments are defined in the dependent claims. Aspects, embodiments and examples disclosed herein, but not falling under the scope of claim 1, do not form part of the invention. This applies in particular to the methods described herein.

[0011] By providing for a second stimulus to be delivered in the neural refractory period following the first stimulus, the present invention provides for de-correlated, or less correlated, fibre responses to be evoked by such stimuli.

[0012] The sequence of neural stimuli may comprise more than two stimuli, each being delivered in the refractory period following a previous stimulus in the sequence.

[0013] The sequence of neural stimuli may comprise stimuli of ascending amplitude.

[0014] The sequence of neural stimuli is applied sequentially by more than one electrode. In such embodiments, the second stimulus is preferably delivered at a time after the first stimulus which allows for cessation of the first stimulus and allows for propagation of a first neural response evoked by the first stimulus from the first electrode to the second electrode, so that the second stimulus is delivered during a refractory period of neurons proximal to the second electrode after activation of those neurons by the evoked neural response from the first stimulus. Additionally or alternatively, in some embodiments the sequence of neural stimuli may be applied by consecutive electrodes positioned along an electrode array.

[0015] The timing of the respective stimuli in the sequence is controlled in order to cause spatiotemporal alignment of the respective evoked responses propagating in a first direction along the nerve fibre to thereby cause correlation and summation of evoked responses in the first direction, while causing spatiotemporal misalignment of the respective evoked responses propagating in a second direction opposite the first direction along the nerve fibre, to thereby decorrelate evoked responses propagating in the second direction. It is advantageous to decorrelate evoked potentials propagating toward the brain, where it is desired to avoid or minimise any percept from the stimuli.

[0016] In some embodiments of the invention, the sequence of neural stimuli may be followed by a single stimulus which is not applied during the refractory period of any preceding stimulus, and which is not closely followed by any subsequent stimulus in the refractory period of the single stimulus. Such embodiments may be applied in order to enable an evoked response measurement to be made following the single stimulus, to enable ongoing refinement of stimulus parameters of the sequence of neural stimuli.

Brief Description of the Drawings

[0017] An example of the invention will now be described with reference to the accompanying

drawings, in which:

Figure 1 illustrates an implantable device suitable for implementing the present invention;

Figure 2a shows the Aβ response amplitude growth functions for stimulation of the sheep spinal cord at 40, 80 and 120 μs, while Figure 2b shows the compound action potential recorded at equivalent charges for the three different pulse widths;

Figure 3 illustrates summation of a sequence of overlapped neural responses;

Figure 4 is a schematic illustration of a potential pulse sequence and the amplitude growth curve associated with the sequence;

Figure 5 illustrates ERT responses to bursts of stimulation with differing frequencies;

Figure 6 illustrates a stimuli scheme to generate stimuli which result in synchronising Aβ activation in the antidromic direction and a desynchronising activity in the orthodromic direction;

Figure 7 illustrates experimental results obtained by applying a series of four stimuli of ascending amplitude on four adjacent electrodes to a sheep spinal cord;

Figure 8 illustrates experimental results obtained in response to stimuli bursts of different inter-stimulus intervals; and

Figure 9 illustrates a suitable feedback controller for controlling the parameters of the stimuli burst in an automated manner.

Description of the Preferred Embodiments

[0018] Figure 1 illustrates an implantable device 100 suitable for implementing the present invention. Device 100 comprises an implanted control unit 110, which controls application of a sequence of neural stimuli in accordance with the present invention. In this embodiment the unit 110 is also configured to control a measurement process for obtaining a measurement of a neural response evoked by a single stimulus delivered by one or more of the electrodes 122. Device 100 further comprises an electrode array 120 consisting of a three by eight array of electrodes 122, each of which may be selectively used as either the stimulus electrode or sense electrode, or both.

[0019] The activation and simultaneous suppression of different areas of tissue is highly desired for treatment of a number of neurological disorders. The activation of micturition or defection without contraction of the sphincter is highly desirable for treatment of incontinence. The goal of stimulation of the spinal cord is to block transmission of pain signals from Aδ and C fibres, via the inhibitory effect of the activation of Aβ fibres. The ascending Aβ fibres produce a

psycho-physiological response which results in the paraesthesia (described as tingling by recipients). A number of ways to reduce or eliminate this effect have been suggested. It has been reported that burst mode stimulation or continuous stimulation at high frequencies can produce pain relief without accompanying paraesthesia, however the mechanisms are not clear.

[0020] One possible explanation is that the high frequency stimulation results in a highly uncorrelated neural firing pattern in the ascending Aβ tracts. High frequency stimulation results in the continuous activation of the fibres and produces a randomised firing pattern. The recovery time (refractory period) between each fibre is slightly different and if a depolarisation potential is present as the fibre comes out of refractory period, it will depolarise again, but not synchronised with other fibres which may still be in their refractory periods. The net result is a randomisation of the firing pattern and a return of the stochastic response in the fibre.

[0021] Measurements of the evoked neural response provide a direct measure of the degree of correlation of the firing pattern. Figure 2a shows the Aβ response amplitude growth functions with respect to stimulus amplitude, for stimulation of the sheep spinal cord at 40, 80 and 120 μs. The recruitment is related to charge and so stimulation at 1 mA for 120 μs produces an equivalent charge for stimulation at 3 mA for 40 μs, with vertical lines highlighting two respective points of equal charge delivery for each trace. Figure 2b shows the compound action potential recorded at equivalent charges for the three different pulse widths. The peak height is smaller and the evoked response peak is wider at the equivalent charge for the longer pulse width than for the shorter pulse width, and this is indicative of a less correlated evoked response.

[0022] The probability of any single fibre responding is a function of the properties and history of the fibre and the amplitude of the current pulse. Although short and long pulses for an equivalent charge may recruit the same number of fibres the longer lower current amplitude pulse will recruit the fibres over a longer time scale than the higher current shorter pulse width.

[0023] Patients report a preference for stimulation with longer pulse widths and the reason for this preference may be because the perceptual side effect is lower, because there is a lower correlation between the fibres firing. Given this observation, highly uncorrected responses may give rise to much lower psycho-physical side effects such as tingling sensations and paraesthesia. The evoked responses measured for the longer pulse widths are broader in Figure 2b, indicating less correlation in the firing pattern.

[0024] Measurement of the evoked response provides a unique way to assess the degree of correlation amongst fibres in a group, as the peak width and amplitude of the measured response directly relates to the degree of timing synchronisation of the single fibre action potentials which sum to form the compound action potential. The goal of stimulus design is to achieve a high level of recruitment at the segmental level and a low level of correlation for the ascending segments. The neural response measurement obtained at each sense electrode may be conducted in accordance with the techniques set out in Daly (US 2007/0225767).

Additionally or alternatively, the neural response measurement may be conducted in accordance with the techniques set out in Nygard (US Patent No. 5,758,651). Additionally or alternatively, the neural response measurement may be conducted in accordance with the techniques set out in the Australian provisional patent application No. 2011901817 filed simultaneously herewith in the name of National ICT Australia Ltd entitled "Method and apparatus for measurement of neural response" and subsequently published as WO 2012/155183.

[0025] The degree of correlation within an evoked response can be measured with such techniques, and pulse sequences can be designed to produce evoked responses of a desired character. A typical recruitment curve is shown in Figure 2a. The strength of the Aβ potentials directly relates to the number of fibres recruited, and therefore stimulation at successive larger and larger pulse amplitudes will recruit successively more fibres. If the pulses are timed so that they occur within the refractory period of the excited neurons from the previous pulse then different sub populations of neurons can be selected with each pulse.

[0026] The timing of each pulse can be so arranged so that the travelling CAPs from each individual pulse cancel each other as they sum at some distance from the stimulation site. This indicates the degree of desynchronisation between the fibres, and as the sensory input is based on correlation of firing patterns the sensation (paraesthesia) is reduced. However, the activation of the inhibitory effect of the Aβ fibres at the segmental level is not reduced, permitting Aβ inhibition of Aδ and C propagation to occur, as desired.

[0027] Figure 3 illustrates the principle of applying a sequence of neural stimuli and allowing the respective evoked responses 302, 304, 306 to propagate along the fibre. The numerical summation of five such partially overlapping compound action potentials, of which only three appear in Figure 3, is shown at 308. Fig 3 shows the effect of the summation of the evoked response from five pulses with the timing intervals between the pulses so arranged as result in the arrival of the evoked response waveform at a designated point along the electrode array such that the averaged signal recorded at that point is minimised. For the data shown in Figure 3 the timing difference between each cathodic pulse is 0.3 ms.

[0028] Figure 4 is a schematic illustration of a potential pulse sequence (lower) and the amplitude growth curve associated with the sequence (upper). Current levels A-C are represented on both portions of Figure 4. The initial pulse of amplitude A can be expected to recruit only a portion of the available population. Application of the subsequent stimulus of greater amplitude can then be expected to recruit a further portion, but not all, of the available neural population, even though stimulus B is applied during the refractory period after stimulus A. Similarly, stimulus C can be expected to recruit a further portion of the available neural population. C may be applied during the refractory period of stimulus B only, or possibly within the refractory period of both stimuli A and B. The sequence of neural stimuli A-B-C can thus be expected to recruit perhaps a similar amount of the available neural population as would stimulus C if applied alone, however the progressive recruitment of portions of the neural population at progressive times provides for a significantly decorrelated evoked response as

compared to the response resulting from a single stimulus of amplitude C.

[0029] The concept of a selection of stimulus sequences based on the ERT recorded parameters can be greatly extended. For instance the example of Figure 4 demonstrates achieving an uncorrelated ensemble response in the fibre population being stimulated.

[0030] Figure 5 illustrates ERT responses to bursts of stimulation with differing frequencies. The degree of correlation can be inferred from the ERT signal. A normal stimulus can be used to assess the stimulation response amplitude in the absence of any further desynchronising pulses. The amplitude of the single probe pulse is adjusted to represent the total charge delivered over time for the corresponding desynchronising pulse train. The amplitude of the response measured from the single probe pulse represents a fully synchronised response. The desynchronising pulse train is then output and the response measured. The ratio of the two responses is proportional to the level of synchronisation and so can be used as a control parameter for adjusting the characteristics of the device. For instance the control parameter may be adjustable by the patient to allow the patient to adjust the level of perceived paraesthesia. The control variable may also be used by the system for detection of a change of state in the neural tissue for a diagnostic purpose.

[0031] A single non-decorrelating stimulus can be applied to the nerve by the device periodically or occasionally in order to elicit an evoked response which is then used as the input to the control loop. This probe stimulus can be adjusted so that its charge is equivalent to the charge presented by the desynchronising stimuli. The frequency of the probe pulse to desynchronising pulses can then be adjusted to minimise the perceptual side effects. The probe frequency can also be adjusted on demand, responding more rapidly to changes in movement, for example.

[0032] Conduction of the compound action potentials occurs both orthodromically (up the spine) and antidromically (down the spine). Careful choice of stimulus design can be used to create a situation where the degree of synchronisation can be different in both directions, and controllably so. For example it may be desirable to generate stimuli which result in synchronising Aβ activation in the antidromic direction and a desynchronising activity in the orthodromic direction. One possible scheme for doing this is illustrated in Figure 6. A stimulus pulse, preferably biphasic, is discharged at an electrode (electrode '0' indicated on the left side of Figure 6). At some time interval later a 2^{nd} stimulus pulse is discharged between another two electrodes. For convenience this is illustrated in Figure 6 as the electrode (number "1") adjacent to the first electrode. The 2^{nd} discharge is arranged so that it occurs in time and place such that its resultant CAP propagation to an electrode (e.g. '+6') in one direction (the upward direction in Figure 6) sums with each other evoked CAP. In contrast, in the other direction (the downward direction in Figure 6), the respective CAPs are misaligned and decorrelated for example when observed at electrode '-3'.

[0033] A possible means but not the only means to achieve such directional selectivity of CAP correlation is to arrange a series of stimulus pulses with an interpulse interval equal to the

difference in propagation time required for desynchronisation of the CAP in the ascending direction.

[0034] Note that the order in which the stimuli are presented does not need to be sequential. The amplitudes of the individual stimuli can also be varied according to the scheme of Figure 4. The timing of presentation can also be dithered to adjust the timing.

[0035] Figure 7 illustrates experimental results obtained by applying a series of four stimuli of ascending amplitude on four adjacent electrodes to a sheep spinal cord. Each stimulus was a tripolar stimulus for which the respective centre electrode was, in order, electrode E7, E8, E9 and E10, being the four centrally positioned electrodes of a 16 electrode linear electrode array. Each stimulus was biphasic with each phase having a pulse width of 20 μs, and the interphase gap being 10 μs. The stimuli were of ascending amplitude, being 2 mA, 2.5 mA, 3 mA and 3.5 mA respectively. The inter-stimulus interval between each successive pair of stimuli on the respective electrodes was 33 μs, so that the pulse-to-pulse time was 83 μs, to optimally correlate the net evoked response in the antidromic (ie caudal) direction. As can be seen in Figure 7 the antidromic response 704 measured on electrode E16 was well correlated from the four constituent parts, and is of large amplitude. In contrast, the four orthodromic responses were effectively decorrelated and produced a net response 702 measured at electrode E3 which was of much reduced amplitude compared to response 704 travelling in the opposite direction, even though both were produced by the same burst of four stimuli.

[0036] Figure 8 shows the responses measured at different inter-stimulus intervals. As can be seen the inter-stimulus interval strongly affects efficacy of this technique, and so preferred embodiments provide a feedback loop in order to optimize this parameter, and all other stimulus parameters, in setting up the stimuli burst. Figure 9 illustrates a suitable feedback controller for controlling the parameters of the stimuli burst in an automated manner, so as to use the measured evoked responses in each direction to determine the stimulus parameters required to achieve a desired directional effect. Such automated feedback permits the relatively large parameter space to be efficiently explored to identify optimal stimuli burst parameters.

[0037] It will be appreciated by persons skilled in the art that numerous variations and/or modifications may be made to the invention as shown in the specific embodiments without departing from the scope of the invention as defined by the claims. The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive.

REFERENCES CITED IN THE DESCRIPTION

This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all

liability in this regard.

Patent documents cited in the description

- EP2243510A [0007]
- US20070225767A [0024]
- US5758651A [0024]
- AU2011901817 [0024]
- WO2012155183A [0024]

Non-patent literature cited in the description

- **MAHNAN, A et al.** Measurement of the current-distance relationship using a novel refractory interaction techniqueJ. NEURAL ENG., 2009, vol. 6, 3036005- [0008]

Krav

1. En enhed (100) til påføring af en neural stimulus, hvor enheden (100) omfatter:
mindst to elektroder (122), der er konfigureret til at blive placeret langs en neural bane med en fiberpopulation; og en styreenhed (110), der er konfigureret til: at anvende en sekvens af terapeutiske neurale stimuli, hvor sekvensen af stimuli omfatter en første stimulus og en anden stimulus, som leveres inden for en refraktionsperiode for fiberpopulationen efter den første stimulus, hvori sekvensen af neurale stimuli anvendes sekventielt på mere end én af de mindst to elektroder (122), hvori stimulusparametre for den anden stimulus varierer fra stimulusparametrene for den første stimulus på en måde, så den anden stimulus kan rekruttere en videre del af fiberpopulationen end den første stimulus; og kontrollere timingen for de respektive stimuli i sekvensen for at forårsage spatiotemporal justering af respektive fremkaldte reaktioner, der spredes i en første retning langs nervefiberen for derved at forårsage korrelation og opsummering af de fremkaldte reaktioner i den første retning, mens der forårsages spatiotemporal fejljustering af de respektive fremkaldte reaktioner, der spredes i en anden retning modsat den første retning langs nervefiberen for derved at dekorrelere de fremkaldte reaktioner, der spredes i den anden retning.

2. Enheden i krav 1, hvor sekvensen af neurale stimuli omfatter mere end to stimuli, der hver leveres i en refraktionsperiode efter en tidligere stimulus i sekvensen.

3. Enheden i krav 1 eller krav 2, hvor sekvensen af neurale stimuli omfatter stimuli med stigende amplitude.

4. Enheden i krav 1, hvor styreenheden (110) er konfigureret til at levere den anden stimulus på et tidspunkt efter den første stimulus, hvilket tillader ophør af den første stimulus og tillader spredning af en første neural reaktion, der er fremkaldt af den første stimulus fra en første elektrode (122), til en anden elektrode (122), så den anden stimulus leveres af den anden elektrode (122) under en refraktionsperiode for neuroner proksimalt for den anden elektrode efter aktivering af disse neuroner via den fremkaldte neurale reaktion fra den første stimulus.

5. Enheden i ethvert af kravene 1 til 4, hvor styreenheden er konfigureret til at anvende sekvensen af neurale stimuli via efterfølgende elektroder (122), der er placeret langs et elektrodearray (120).

6. Enheden i ethvert af kravene 1 til 5, hvor den første retning er kaudal.

7. Enheden i ethvert af kravene 1 til 6, hvor styreenheden (110) desuden er konfigureret til at anvende en enkelt stimulus uden for refraktionsperioden for enhver forudgående stimulus, og som ikke umiddelbart efterfølges af nogen efterfølgende stimulus i refraktionsperioden for den enkelte stimulus for at muliggøre gennemførelse af en måling af fremkaldt reaktion efter den enkelte stimulus.

8. Enheden i krav 7, hvor styreenheden desuden er konfigureret til at bruge målingen af fremkaldt reaktion

til feedbackkontrol af stimulusparametre for sekvensen af neurale stimuli.

DRAWINGS

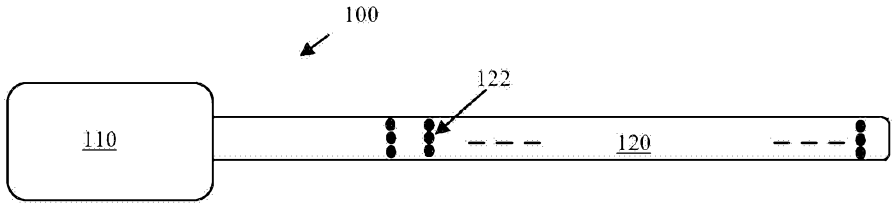

Figure 1

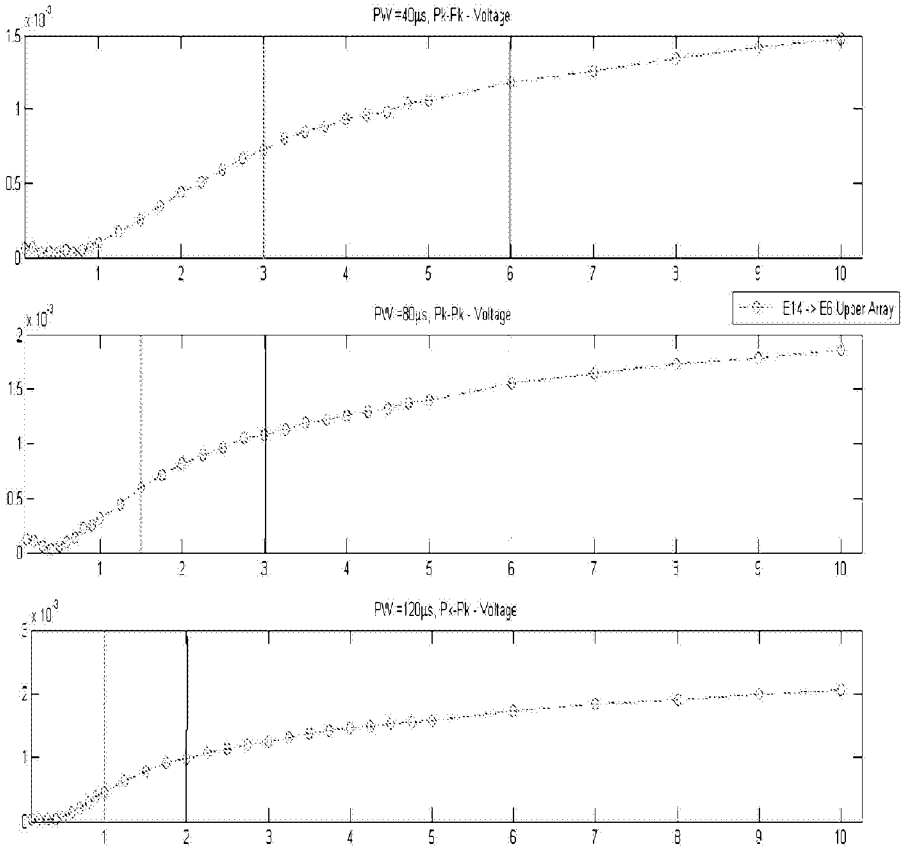

Figure 2a

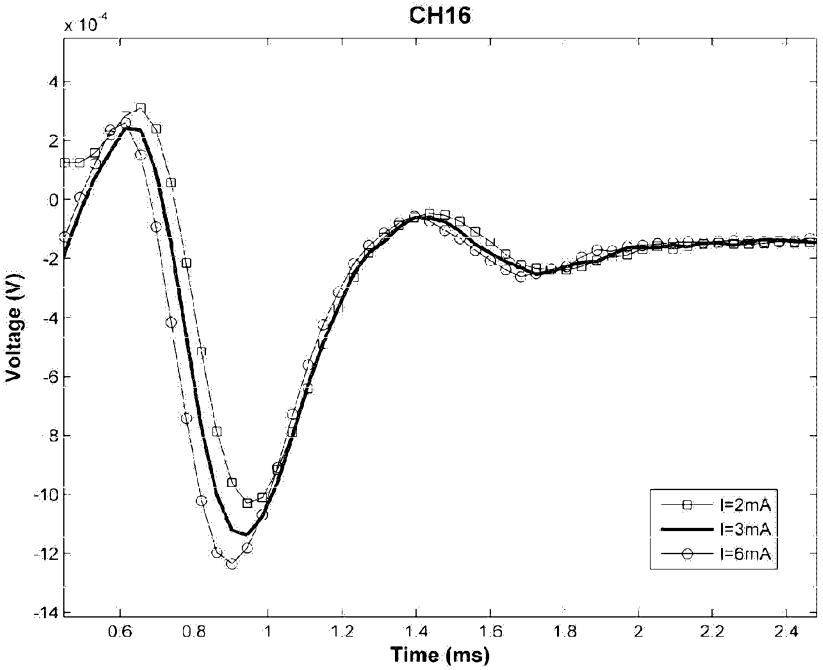

Figure 2b

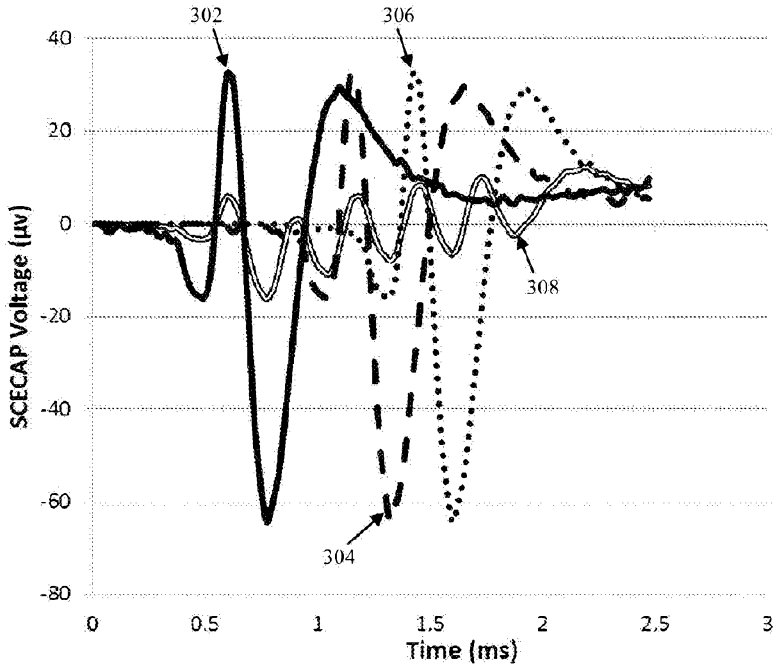

Figure 3

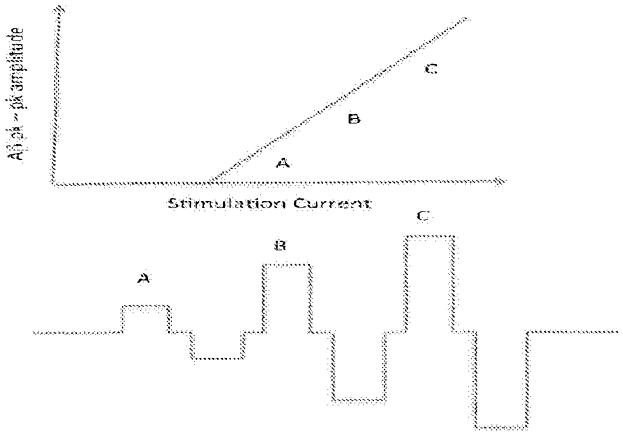

Figure 4

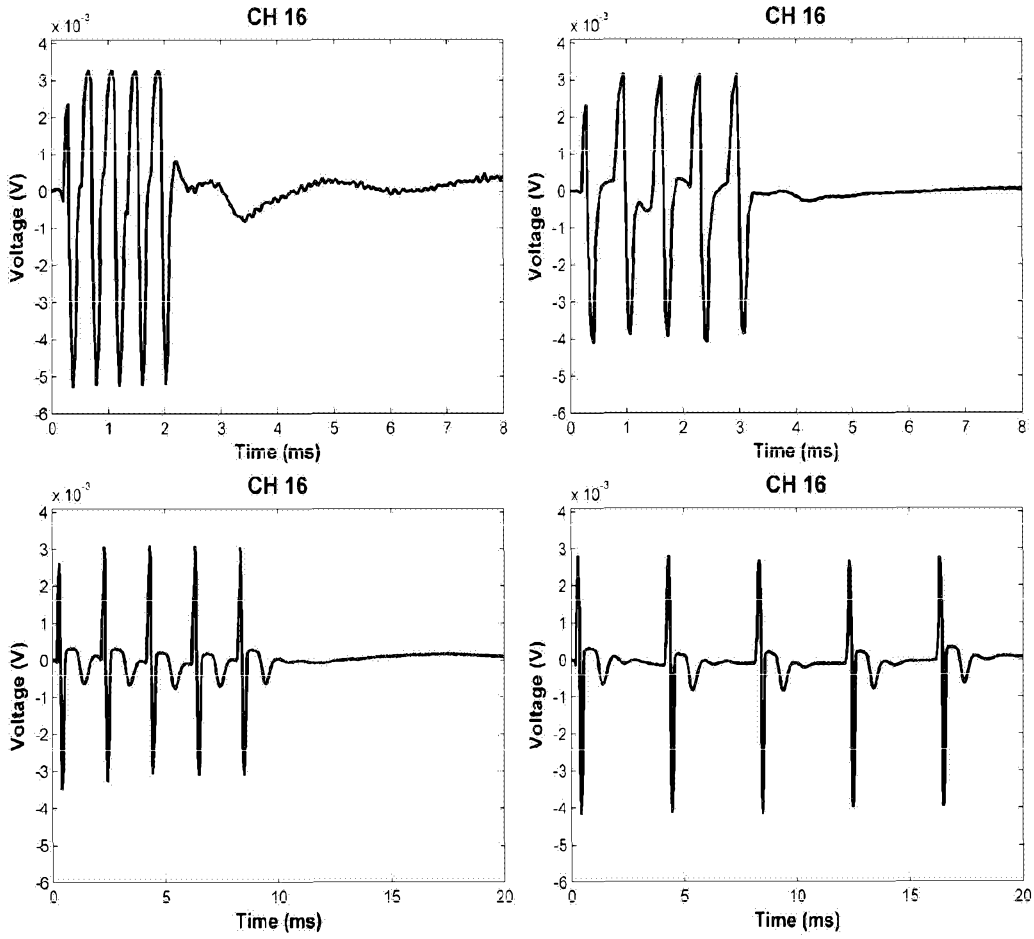

Figure 5

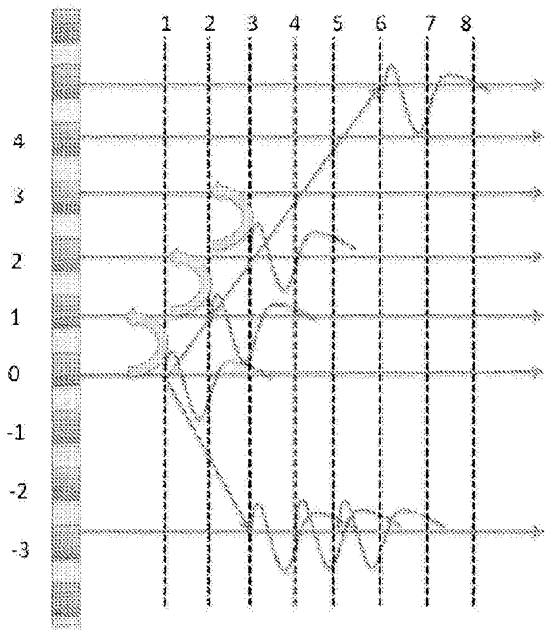

Figure 6

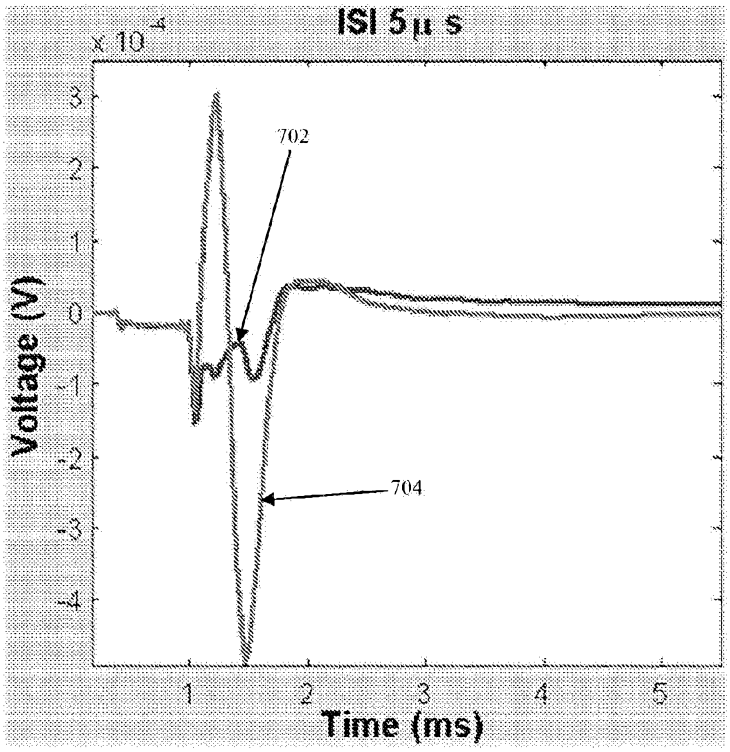

Figure 7

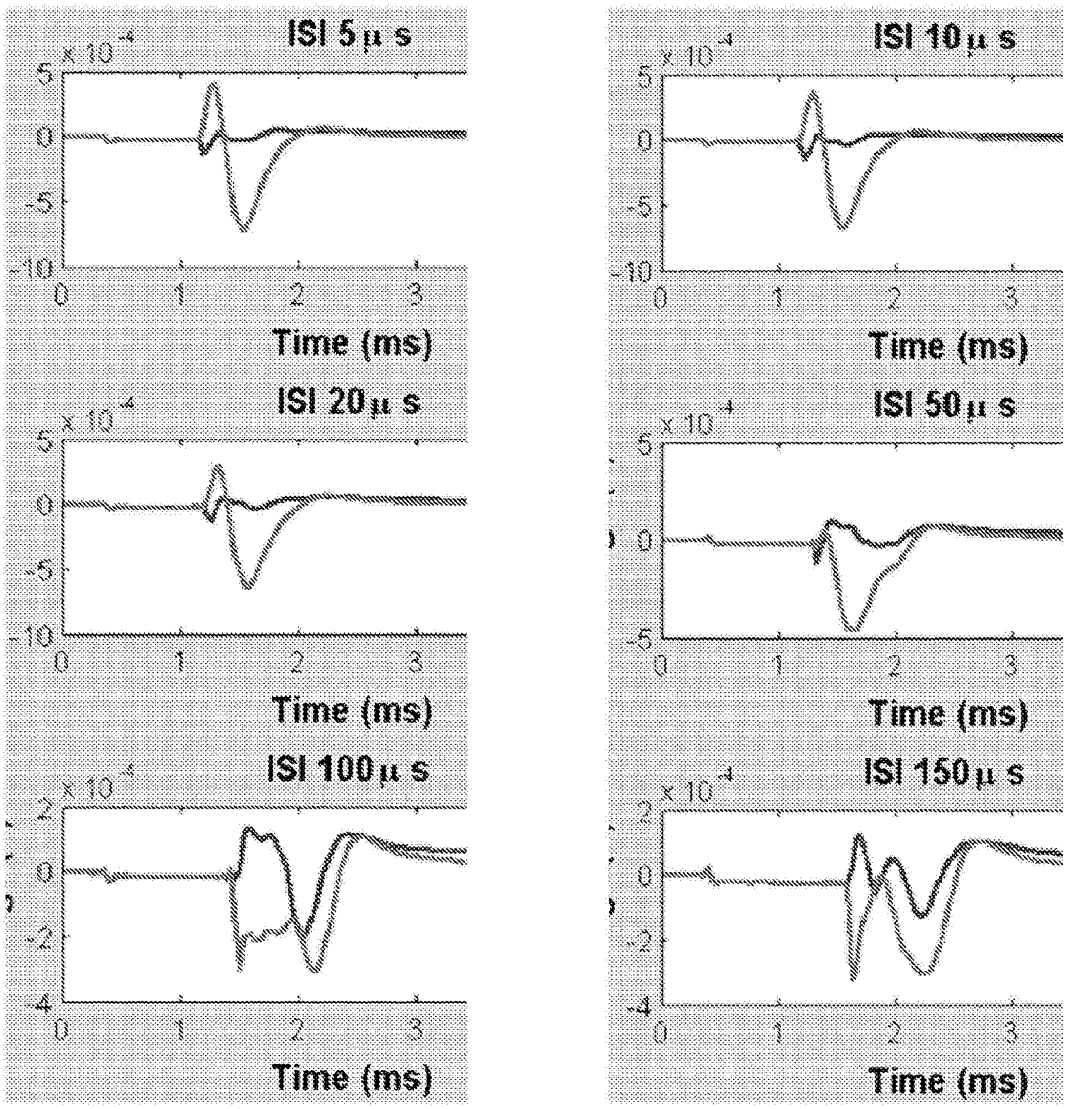

Figure 8

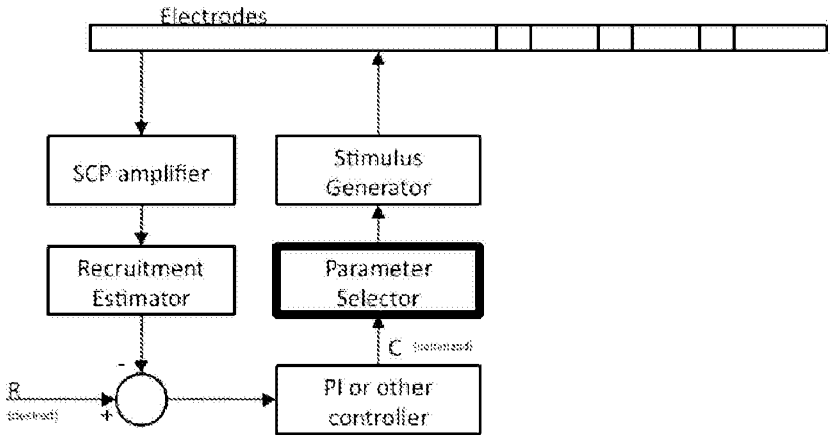
Electrodes
SCP amplifier
Stimulus Generator
Recruitment Estimator
Parameter Selector
C
R
PI or other controller

Figure 9