IMMEDIATE EFFECTS OF SPINAL CORD STIMULATION

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ABSTRACT

Clinical and Neurophysiological studies of the immediate effects of spinal cord stimulation have been conducted in a group of 15 patients with implanted systems for epidural stimulation. The study consisted of patient reports of sensation immediately after the beginning of stimulation and during changes of the parameters of electrical stimulation. Neurophysiological analyses were made of the effects of single stimuli and trains of stimuli delivered through the system as conditioning stimuli on repetitively elicited phasic tendon jerks and tonic vibratory responses.

All patients consistently reported sensory effects of spinal cord stimulation. In addition, the stimulation also produced a facilitory effect on segmental stretch reflexes. Based on the spatial relationship of the stimulating electrode to anatomical structures of the spinal cord, together with patient reports and our own neurophysiological measurements, we concluded that spinal cord stimulation can activate specific structures of the spinal cord.

INTRODUCTION

The application of continuous trains of electrical stimuli to the dorsum of the spinal cord of humans through subdural or epidurally placed electrodes has been applied for the alleviation of chronic intractable pain since the technique was described by Shealy et al., (1). For the past five years, the technique has also been applied to the modification of motor disabilities as well, following the observation that dorsal column stimulation, applied to alleviate pain, also enhanced motor performance (2). This observation has been independently verified by Illis (3), by Dooley (4), and by Sharkey (5). The method can now be considered to be one of the methods of choice for modification of motor control in patients with selected degrees and kinds of upper motor neurone disorders. How this stimulation works is not clear, however.

Looking back to the application of this method to pain studies, some relevant observations have been made in patients and experimental animals as to the mechanisms of pain relief by such chronic electrical stimulation. In particular, Larson et al. (6) observed that electrical stimulation applied subdurally over the dorsal columns, effective in relieving pain in 17 of 18 patients, could in some instances create abnormal cutaneo-muscular and exaggerated stretch reflexes as well as reduced sensation. The stimulation also diminished the amplitude of somatosensory evoked potentials in each of the 6 patients studied. In exploring the underlying physiological mechanisms, electrodes were chronically implanted over the thoracic portion of the spinal cord in 15 monkeys. Subsequent examinations revealed that the application of 100 Hz continuous stimulation to the spinal cord blocked the afferent transmission through the spinal cord and to the brain, but facilitated the efferent transmission from the motor cortex to the limb muscles.

The clinical criteria are now known for the use of Spinal Cord Stimulation (SCS). However, the mechanisms of action of this stimulation remain unknown. There is some uncertainty as to what degree the effects of SCS are non-specific, due to the placebo effect, and how much are due to modification of specific mechanisms within the spinal cord. Therefore it is essential to seek evidence of any specific propriospinal conditioning effects of SCS on segmental reflexes. Our use of chronic SCS applied through epidural electrodes has been directed toward the modification of impaired motor control in patients with spasticity. In this report, we shall describe the effects of SCS, both as reported by the patients, and as evaluated by the conditioning effect of spinal cord stimulation on phasic and tonic stretch reflexes.

RESULTS

Our observations were made in 18 patients with chronic upper motor neurone disorders tested with SCS, 15 of whom ultimately had the stimulation system permanently implanted (5). Continuous, rectangular monopolar stimulation pulses, applied at a rate of 20 to 75 Hz and 200 to 400 microseconds duration was applied to the patients through 1 mm by 5 mm platinum electrodes placed outside the dura, within the spinal canal (7)

When the stimulus was applied at a rate of 30 to 50 Hz with a slowly increasing strength, the patients typically reported that they at first feel a tingling sensation, difficult to localize and define at low intensities, but becoming more definite as the intensity is raised. Determination of the precise threshold level of sensation was difficult, both because of the nature of the sensation produced at low levels, and because the effect builds during the first few tens of seconds of application. Once a threshold level was established, this increasing effect could be demonstrated by turning the stimulus off for a few moments, then returning the intensity to a fixed level slightly above the threshold. The patient usually felt a slow increase in the sensation for 10 to 20 seconds. Localization of the initial sensation depended on the placement of the electrodes, both laterally and vertically. The location of the cathode was most critical, with the placement of the anode being of almost no consequence unless it interfered with the creation of the stimulus current density pattern from the cathode. If the cathode was displaced to one side or the other, the sensation was strongest from that side.

Although the initial sensation may be felt only near the cathode site, if the level is increased slightly above the threshold, the patients frequently reported feeling the tingling or prickling sensation in both legs and feet (if the electrode is properly centered over the spinal cord), in addition to the sensation first felt in the trunk. When such sensation was present at all, it frequently required some time to appear, perhaps as much as several days of continuous stimulation. If the cathode was located high enough in the spinal canal, e.g., T1, the tingling sensation might be felt in the arms and hands as well. When the cathode was displaced too far to the side of the spinal canal, the effects characteristic of SCS were superceded by specific, localized, low threshold stimulation of sensory nerve filaments.

Once the patients became accustomed to the sensation, almost all were able to accurately report any changes in the energy of stimulation, whether due to changes in the rate, amplitude or pulse width, and are able to report when the stimulus strength is reduced to a level 5 to 10% below their previously determined threshold. However many reported some carry-over effects of the stimuation, including certain transient sensory events, for up to a day if the stimulation had been applied for more than several days prior to turning it off.

Although it is not completely clear which set is optimal for clinical application, the effects of adjustment of the parameters of stimulation generally were as expected. When stimulating at low rates (up to 10-15Hz), the patients perceive the stimulus as a series of pulses. When stimulating at intermediate rates (15-25 Hz), the stimulus quality was frequently described as a rough sort of vibration. At higher rates from 25 up to about 50 Hz, the patients perceived a smoother vibration. Finally, above about 50 Hz, the patients were unable to discern any changes in the quality of sensation, but report only the changes in energy of stimulation resulting from the higher rate. Adjustment of the amplitude and pulse width seem to be completely interchangeable in producing a given quality of sensation, within the normal range of amplitudes.

For routine usage, the stimulus amplitude was adjusted to a level which was comfortable for the patient, yet effective in modifying motor performance. This was frequently at or just below the threshold of sensation. When the stimulus was adjusted to levels above the threshold, it quickly became uncomfortable to the patients, with a change of only 5 to 10% above the threshold, in many cases. In some instances, the stimulus was reported as painful, but more often, the discomfort seemed to be associated with the muscle twitches and muscle rigidity which resulted. Since the electrodes were typically located in the upper thoracic area, the first such uncomfortable sensation was often a tightness of the chest.

The effects of SCS can be surprising to the patient as well as to the physician, both in its augmenting effects, and in some instances in its interfering aspects with desired motor performance goals. On at least two occasions, when patients (R.B. and M.A.) have attempted to adjust the amplitude of stimulation by themselves and have mistakenly turned the stimulator all the way up, a generalized rigidity has resulted which incapacitated them, and they required the assistance of another individual to turn the unit back down. In one patient (T.M.), an increase of the stimulus to abnormally high levels while in the sitting position resulted in a smooth, tonic extension of the knee. In another patient (H.F.), from whom the electrodes were subsequently removed, an increase in the frequency of stimulation resulted in an increasing interference with normal volitional control of hand grasping functions.

Effects of Spinal Cord Stimulation on Segmental Reflexes: In an attempt to evaluate the effects of SCS independently of patient observations we have analyzed the conditioning effects of single pulses on repetitively elicited phasic reflex, and the effect of a train of stimuli on tonic stretch reflexes. It is well known that phasic as well as tonic stretch reflexes are under the influence of descending excitation and inhibition as well as facilitation and suppression. Therefore we examined whether SCS could activate or modify any of those descending mechanisms.

Conditioning Phasic Reflexes: We evaluated the ability of single pulses to condition the phasic stretch reflex in the following manner. Using a constant tendon tap produced by an electrodynamic hammer, triggered at a rate of 1 Hz, the full-wave rectified tendon tap responses were integrated for a period of 20 to 30 ms at the latency appropriate for the patient, and the resultant value averaged for 20 responses. Continuing the constant rate, constant force tendon taps, single pulses were applied via the epidural electrode at various amplitudes and at various delays before and after the tap. The average of the full-wave rectified, integrated values for the trial with the conditioning stimulus was then compared to the control value derived prior to the conditioning set. Figure 1 shows the results of a series of trials for one of the 5 patients so evaluated. When the amplitude of the tendon jerk

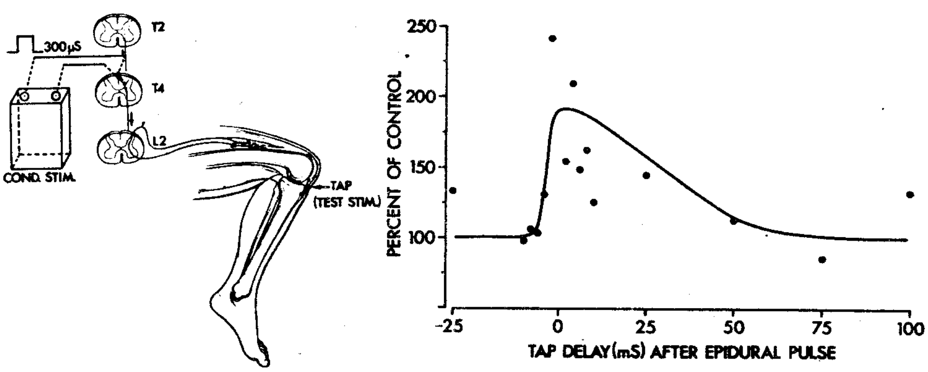

Figure 1. Changes in Phasic Stretch Reflex Responses Induced by SCS. With the procedure schematically shown on the left, the percentage change in the tendon tap responses is indicated on the vertical scale, versus the delay between the conditioning and test stimuli on the horizontal, in a spinal cord injury patient (H.F.). Each point represents the percentage change in the average response to 20 taps of the left patella. The stimuli were 200 microsecond pulses applied through the electrodes with the cathode at T2.

was sub-maximal, and when the amplitude of the conditioning stimulus was optimal (somewhat above threshold of sensation for the single pulses, which was in turn, higher than the value required for continuous stimulation at, e.g., 30 Hz), there was a specific period during which an epidural conditioning stimulus could facilitate the tendon tap response, typically from about 15 to 50 mS after the tendon tap. If higher strength stimulation was used, a generalized alerting reaction took place, and no such time dependence could be demonstrated. If lower levels of conditioning stimulation were used, there was no consistent effect on the tendon tap responses.

Conditioning Tonic Reflexes: With the use of vibration, we have also demonstrated that epidural stimulation can facilitate a tonic reflex, such as the Tonic Vibratory Reflex (TVR). Estimating the magnitude of the TVR by averaging 50, 200 mS samples of full-wave rectified, integrated EMG signals taken while vibrating, the response to vibration alone and with the addition of epidural SCS can be compared. If the conditioning stimulus was relatively weak (at or near threshold), no effect can be seen. However, when the stimulus was stronger, near the patient's tolerance level, a facilitation of the TVR could be seen. Figure 2 shows the results of one such study.

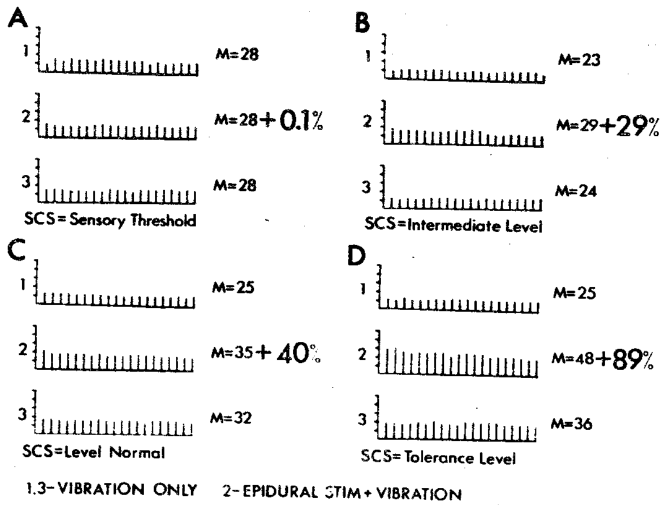

Figure 2. Facilitation of the Tonic Vibratory Reflex with SCS. The four sets shown represent four trials in which the vibration was conditioned with increasing amplitudes of SCS. The pulse width and frequency were the same as those normally used by the patient.

Direct Stimulation: In addition to the conditioning effects, SCS can produce direct motor effects as well, if higher levels are used. When 200 microsecond pulse width stimuli were delivered at a low rate and intermediate or high amplitude, contractions of the pectoralis muscles and others could be seen. Examination of EMG signals from these muscles revealed a short latency and quick recovery characteristics, which suggested that these contractions are due to the direct stimulation of the motor cells or axons, rather than reflexly induced. In contrast, these single, low repetition rate stimuli were much less effective in producing sensation, requiring much higher intensities to reach threshold and tolerance levels.

DISCUSSION AND CONCLUSIONS

The patients have consistently reported different qualities of sensation produced by changing the position of the electrodes and the parameters of the electrical stimuli. The stimulation produced an immediate effect on sensory structures of the spinal cord at the cathode site. On the other hand, irradiation of sensation to points on the extremities did not seem to depend on the parameters of stimulation. Instead, to achieve irradiation, it was necessary to apply a comfortable level of stimulation for an extended period of time, to allow "temporal summation" to occur. These two observations suggest that the effects of SCS on the posterior portion of the spinal cord do not depend merely on the number of fibers depolarized but also on how long the induced activity has interacted with suprasegmental structures. The dependence of the reported sensation on the characteristics of the stimulus can be understood in terms of the anatomy of the posterior portion of the spinal cord, as shown in Figure 3.

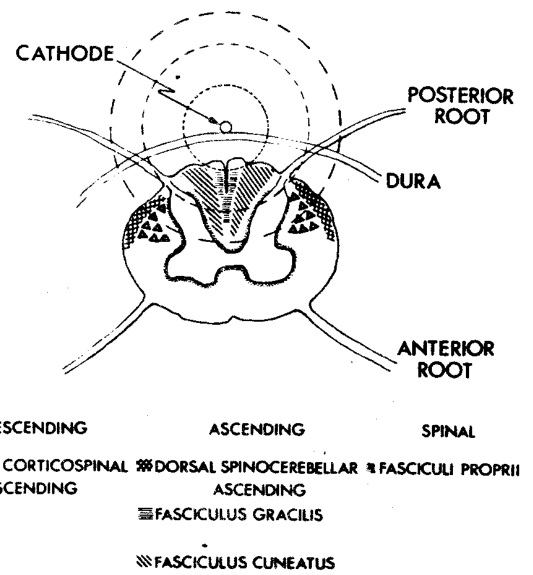

Figure 3. Schematic Representation of the SCS Cathode in Relation to Structures of the Spinal Cord.

Continuous stimulation of low amplitude elicits at first tingling in a similar dermatome, followed after a short time by spreading of the sensation in the trunk and to the extremities.

This suggests that in the main, SCS depolarizes secondary neurons and not primary neurons. The electrodes are placed adjacent to the posterior portion of the spinal cord, near the median posterior sulcus. Considering the electrode location and type of effects produced, we postulate that low amplitude stimulation primarily depolarizes fibers in the posterior columns. Single strong stimuli will elicit muscle twitches localized in the segment closest to the electrodes. These twitches could be due to stimulation of anterior, posterior, or both spinal roots. In our records, the response was a direct motor response, although with other combinations of stimulation parameters and electrode positions, it might be possible to elicit a reflex response.

To assume that SCS selectively stimulates only the fasciculus gracilis and fasciculus cuneatus of the posterior column is not necessary. Under the right combination of stimulus parameters (particularly intensity) and electrode location, the stimulation can be expected to depolarize interneurones in the posterior columns of the grey matter, including primary and secondary sensory neurones, and the fasciculus propriospinalis. With increases in the strength of the stimulus, depolarization can be expected to invade the dorsal spinocerebellar tracts, and with further increase, the descending lateral corticospinal tracts.

Therefore the narrow range of electrical parameters necessary to invoke the full range of sensation and motor effects as well as our clinical observations that facilitory or suppressive effects on motor control are also determined by stimulus parameters suggest that the relation of the spinal cord and the cathode is an important factor in activating different neurophysiological mechanisms.

Supportive evidence for this hypothesized sequence of activation of the tracts can be found in our recordings of the conditioning effects of SCS on stretch reflexes. We have shown not only that there is a facilitory effect of SCS on stretch reflexes, but the temporal characteristics of this effect as well. The relatively slow conduction velocity and the short-lasting effect, together with the fact that the conditioning occurs with no direct motor output, suggests that the diffuse propriospinal interneurone system contributes to the effect of spinal cord stimulation on spinal motor cells. Thus the fact that the facilitatory conditioning effect is reached above the threshold for stimulation of the posterior columns and below the threshold for stimulation of the corticospinal pathways correlates with the patient reports and together correlate with the anatomical features of the posterior portion of the spinal cord. These preliminary data and our interpretation of them are far from conclusive, but may prove useful in the further definition of the anatomical conditions and neurophysiological mechanisms of SCS.

These preliminary observations and data showing the close dependence of the sensory and motor effects on the stimulation parameters, together with supportive anatomical explanations, suggest that spinal cord stimulation does have a specific effect on specific spinal cord structures. How many structures are involved during stimulation and to what extent this effect depends on non-stimulated structures is a question open to further study and discussion.

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