Article abstract

Behavioral psychophysical techniques were used to obtain strength-duration curves for the ulnar nerve at both threshold and suprathreshold levels. The functions well match those obtained with electrophysiologic procedures, but overcome many of the difficulties associated with traditional electrodiagnosis. An alternate means of presenting the data provides a parameter, the critical duration, that describes the ability of the stimulated nerve to integrate or summate energy over time. The very brief critical duration for normal ulnar nerve and the similar functions at threshold and suprathreshold levels suggest possible mechanisms for the transduction and coding of percutaneous electrical stimuli.

Behavioral assessment of peripheral nerve function

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A number of techniques are available for studying the characteristics of peripheral nerves in human subjects.[1] One clinical test for neuropathology is the shape of the strength-duration curve that describes some criterion response of nerve or muscle as a function of the duration of a stimulating pulse.[2] The characteristics of the strength-duration function provide a basis for identifying the type of nerve being stimulated and for assessing its degree of impairment.

To determine such a curve for afferent fibers serving muscles, investigators sometimes use a visual criterion, noting the amount of current or voltage necessary to produce a minimal muscle contraction as the duration of a rectangular-wave stimulus applied to the skin is altered. The shape of the curve permits an indication of whether muscle denervation has occurred. To study afferent fibers, electrodiagnostic techniques are generally employed, determining the strength of a stimulus required to elicit a criterion evoked compound action potential at a convenient recording site proximal to the stimulus.

Among the parameters that can be obtained from strength-duration curves are the threshold for activation of the nerve fibers at different durations[3] and the chronaxie,[4] a parameter that serves to identify the form of tissue being stimulated. Both measures have been used extensively to detect pathologic conditions in nerve fibers.

Electrophysiologic determination of strength-duration curves requires not only carefully calibrated stimulating equipment but complex apparatus for detecting, amplifying, displaying, and recording the weak nerve activity. Furthermore, in order to obtain a suitably strong signal, it is often necessary to use high current levels, which can prove uncomfortable to the patient.

This report presents evidence obtained from normal subjects that behavioral techniques can be employed to determine strength-duration curves similar to those obtained electrophysiologically. The psychophysical data further suggest that increased current levels recruit additional nerve fibers, so that the coding of stimulus magnitude is based on the number of fibers that exhibit a single action potential rather than on the rate or number of such neural responses in the afferent nerves.

Methods. A pair of Grass silver electrodes, 8 mm in diameter, were filled with electrode cream and taped 2.5 cm apart over the ulnar nerve on the volar surface of the forearms of four male subjects ranging in age from 22 to 25 years. The proximal electrode was attached to the cathode of an isolated constant current stimulation system (Electronics for Life Sciences CCS-1) whose parameters were controlled by Tektronix Series 160 waveform and pulse generators.

During each of five sessions in the first experiment, detection thresholds were obtained by an ascending method of limits, five times for each of 12 pulse durations

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ranging from 0.02 to 100 msec (0.02, 0.04, 0.08, 0.2, 0.5, 1.0, 2.0, 5.0, 10.0, 20.0, 50.0, and 100.0 msec). Pulse amplitude was increased in small steps until the subject reported detecting two successive presentations.

In the second experiment, suprathreshold strength-duration curves were determined by having the same four subjects adjust the intensity of electrocutaneous pulses of the same 12 durations until the magnitude of the resulting sensation matched that of an unchanging auditory tone. Every 2 seconds a 500 msec, 1,000 Hz tone at 55 dB sensation level was presented through a pair of headphones, followed by an electrical pulse at the ulnar nerve. Each subject made five matches for the 12 pulse widths, in random order, in each of five sessions.

Results. The sensation produced by these pulses is described as being tactile in quality, rather than painful, and is often compared to being touched by a dull pencil.

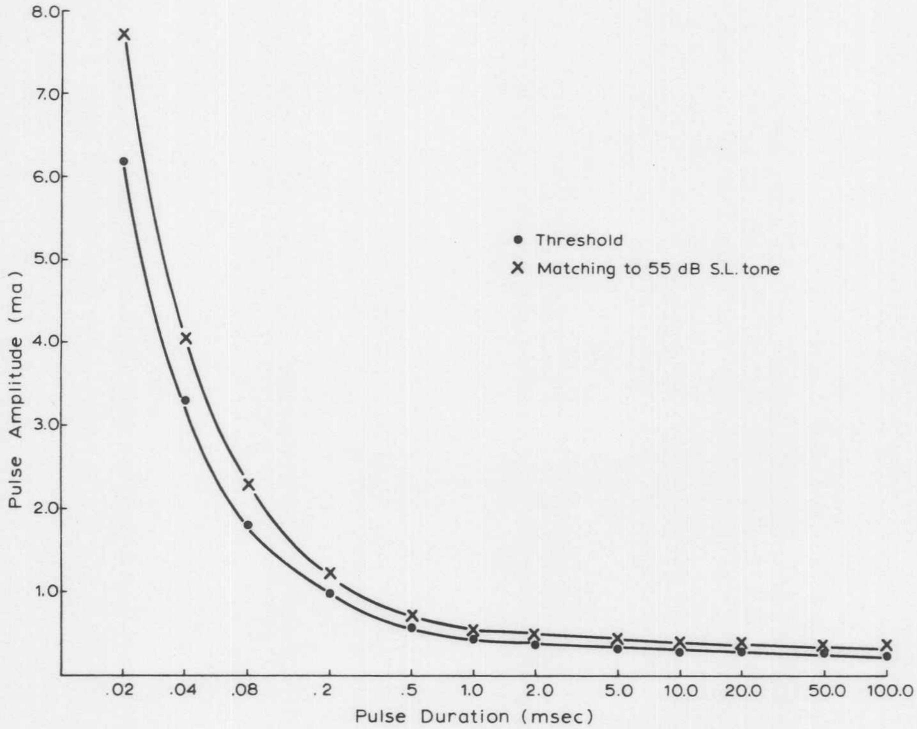

Figure 1. Strength-duration curves illustrating the current required for threshold and for subjective match with a 55 dB sensation level (S.L.) tone as a function of pulse duration for rectangular D.C. electrical pulses on the volar forearm.

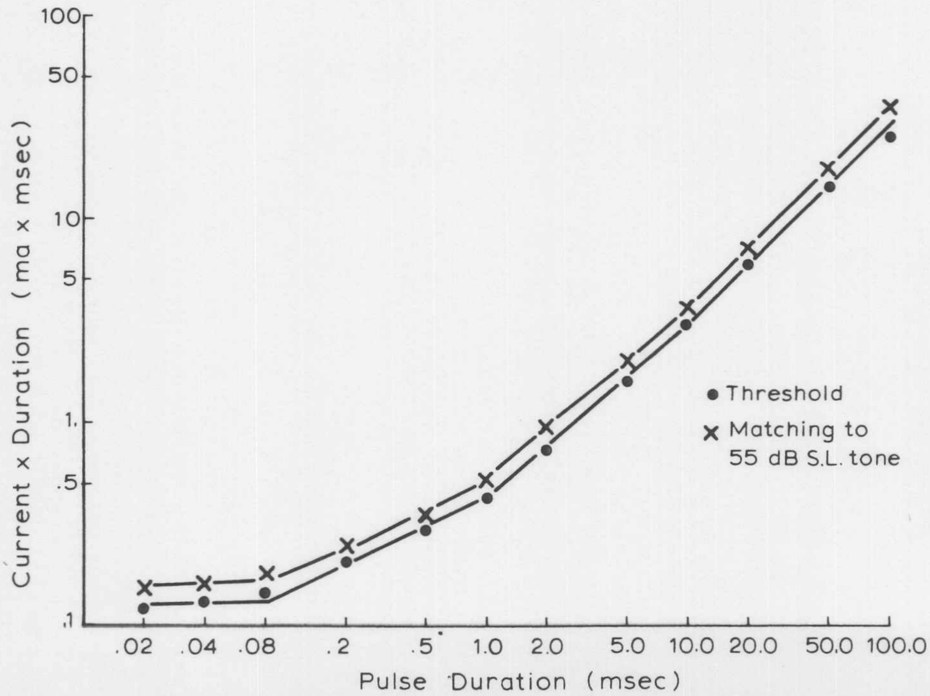

Figure 2. The product of intensity and duration (charge, expressed in microcoulombs) at threshold and suprathreshold levels as a function of pulse duration, showing regions of complete, partial, and no temporal summation.

The thresholds obtained in the first experiment were averaged across trials, sessions, and observers and are presented as the lower curve in figure 1. The threshold current decreased rapidly with increased duration up to about 0.5 msec and changed relatively little beyond that.

The upper curve of figure 1 presents the mean current required at each pulse duration to match the sensation of the constant auditory tone. Observers reported no difficulty in making such cross-modality matches, and the consistency of such a technique, as well as its theoretical validity, has been well-established.[5] Although the amplitude of the auditory stimulus is more than 500 times its threshold value, the very rapid rise of electrical sensation magnitude with physical intensity[6] allows a match to occur when the current is increased by only 25 percent.

Figure 2 presents these same sets of data in an alternate format often used by those studying the temporal summation or integration properties of a sensory modality — the product of intensity and duration (energy) versus duration. In vision, for example, there exists a range of flash durations (t) for which an increase of duration by a certain factor will lower the threshold (I) by that same factor. Thus, a doubling of the time of a flash from 20 to 40 msec will cause it to be just detectable at half the threshold luminance for the shorter presentation. The stimulus energy, the product of luminance and duration, thus remains constant over some range. This trading relationship, called Bloch's law or the Bunsen-Roscoe law, is described by the equation $I \times t = c$ for durations less than t_c, the "critical duration." Many visual studies have shown t_c to be about 50 to 100 msec,[7] although recent experiments[8] suggest that under certain conditions it may be as short as 10 to 20 msec. Studies with auditory or vibratory bursts have found critical durations considerably in excess of 100 msec.[9,10]

In marked contrast, the lower function of figure 2, which presents threshold charge (in microcoulombs) as a function of pulse width, indicates that t_c for single electrical pulses is only 0.08 msec (80 μsec), a value 200 to 2,000 times smaller than that reported in the other modalities. For longer durations, the data were fit by an iterative regression technique with three additional limbs. Two represent periods of partial summation, with one extending to about 1.0 msec and a second to about 10 msec. Beyond that, threshold is independent of pulse within and the function has a slope of 1.0. Similar findings apply to the suprathreshold data, as shown in the upper function in figure 2.

Discussion. A number of features of the behavioral strength-duration curves merit attention. First is their strong resemblance to those obtained in analogous electrophysiologic studies.[11] The lower curve in figure 1 well matches the neurophysiologic curve for large A-fibers, such as those in the underlying ulnar nerve, and the value obtained for chronaxie, about 0.4 msec, is within the normal range reported by investigators using electrodiagnostic methods.[2] The resemblance of the behavioral and physiologic curves, the stability of the former, and the ease with which they can be obtained suggests that psychophysical techniques[12-14] could supplement electrophysiologic ones in clinical studies of peripheral nerve function and pathology.

For example, Heckmann[11] has presented a number of reasons why the "excitability curve" is preferable to the strength-duration curve determined from visual determination of minimal muscle contractions in assessing human peripheral nerve integrity. The excitability curve is obtained by determining the current required at each pulse width to produce a barely visible nerve action potential. Heckmann required currents of 2 ma and greater to produce an excitability curve; the behavioral curve in figure 1 required currents as low as 0.3 ma.

The behavioral method has the same advantages as the electrophysiologic one over the muscle contraction technique (no need to locate the motor point, no need to judge whether a minimal contraction has occurred, no artifact induced by excitation of muscle rather than nerve, and ability to move stimulating electrodes to pinpoint the site of peripheral lesion). Both curves display activity of the nerve fibers alone, permit continual monitoring of changes in activity induced by selective nerve block, and allow clinical determination of both hypoexcitability and hyperexcitability, as well as erratic patterns of excitation.[15-16] The behavioral procedure, however, has the important advantage of simplicity, in that the complex electrophysiologic recording equipment is not needed, patient anxiety can be lessened, and the difficulties inherent in recording weak action potentials are avoided. Furthermore, the much lower currents used and the criteria of threshold and cross-modality match eliminate any pain, thus avoiding both subject discomfort and artifacts in the recordings due to activation of narrow, high-threshold C-fibers.

Since carefully controlled electrical stimuli are being increasingly used, not only in electrodiagnosis but also in the relief of chronic pain,[17-18] the activation of paralyzed muscles,[19] sensory substitution systems,[20] and peripheral studies of the sensory modalities,[21-22] the mode by which such signals are transduced and coded is of considerable interest. Previous research on the detection of brief single electrical pulses applied percutaneously has indicated that such stimuli bypass the cutaneous receptors and directly stimulate the underlying afferent fibers.[13-14] The data from the first experiment are consistent with such a direct mode of activation, since similar curves are obtained when the electrode is on the skin and when it is directly on the nerve.

The upper curve of figure 1, which shows how subjects adjusted an electrical pulse of varying duration until it subjectively matched an auditory tone, indicates that reliable indications of strength-duration functions can be obtained at stronger levels as well. The finding that the shape of the curve is basically unchanged when it moves upward suggests that an increasing number of A-fibers are recruited by the stronger stimulus. It also suggests that the coding of stimulus magnitude involves a form of spatial rather than temporal coding. Subjects may begin to detect the pulses when some critical number of nerve fibers are activated. As current level is increased, these fibers would continue to produce only a single action potential (the all-or-none law of nerve physiology). However, increases in signal strength lead to the activation of more and more fibers whose characteristics, except for threshold or subcutaneous depth, are the same as those of the fibers excited at lower currents, leaving the form of the strength-duration function unaltered at more intense levels. Subjective magnitude could then be coded by the somatosensory system in terms of the number of A-fibers that are fired in synchrony by a single percutaneous pulse.

The alternative means of describing the data from both the threshold and suprathreshold experiments, as illustrated in figure 2, presents the electrical charge of the stimulus meeting the behavioral criterion as a function of the pulse width. This method of presentation has certain advantages over the traditional strength-duration curve. First, the parameter of interest, the critical duration, can be observed directly as the point where the function deviates from a horizontal line (in this case, about 0.08 msec) and requires no calculations as in the case of the chronaxie. Second, this parameter has clearer physiologic implications — it marks the point at which the nerve no longer summates or integrates energy perfectly. At durations less than the critical duration, any increase in pulse width can be perfectly offset by a proportionately equal decrease in stimulating current. If the slope of the function equals unity, the nerve is no longer showing any summation — threshold is constant no matter how long the stimulus is applied (the rheobase). Between these two limits of complete summation and no summation there is often a range of partial summation (demonstrated by a slope greater than zero and less than 1.0) in which the nerve can only partially compensate for changes in pulse duration. Such parameters are expected to be altered in pathologic states — partial summation for denervated muscle, for example, extends beyond 100 msec,[2] compared with about 10 msec for the ulnar nerve preparation studied here.

Furthermore, the critical duration can be examined across modalities in order to compare the integrating properties of peripheral nerves with those of other sensory systems. As noted earlier, critical durations for visual flashes, auditory tones, and bursts of vibration often have been found to exceed 100 msec.[7-10] The value found for electrical stimulation of the skin is only 0.08 msec. This difference seems to arise because electrical stimuli directly excite the nerve fibers. The long values of critical duration were obtained with "adequate" or "natural" stimuli that are transduced by sensory receptors. Receptors, which are capable of summating energy over space, may also be capable of integrating over an appreciable period of time. More important, however, are the central neural consequences of receptor and nerve stimulation. Excitation of a receptor will produce a complex spatiotemporal pattern in both afferent nerve and central loci, whereas a single electrical pulse may establish only one synchronous action potential in some of the underlying nerve fibers. In this case, it is the integrating capacity of the nerve rather than a central mechanism that determines the critical duration, and the parameter can serve as a measure of the sensitivity and integrity of the stimulated tissue.

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