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Authors
Pratt, H
Starr, A
Amlie, RN
et al.

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Article abstract—Somatosensory potentials evoked by mechanical stimulation of the fingernail and electrical stimulation of the nerve in the finger and at the wrist were recorded by surface electrodes over: (1) the digital nerve in the index finger, (2) the median nerve at the wrist, (3) the median nerve at the axilla, (4) the brachial plexus at Erb's point, (5) the cervical cord at C2, and (6) the scalp overlying the somatosensory cortex. Nerve conduction velocities were computed for two portions of the median nerve. Conduction times along the somatosensory pathway between spinal cord and cerebral cortex were also defined.

The mechanically evoked potentials had less temporal dispersion, were of lower amplitude, and occasionally consisted of fewer components than the electrically evoked potentials. Electrical stimulation of the nerve trunk at the wrist evoked some additional components not detected by the other stimulation methods. Nerve conduction velocities and conduction times were comparable among the three methods of stimulation.

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Mechanically and electrically evoked somatosensory potentials in normal humans

H. Pratt, A. Starr, R. N. Amlie, and D. Politoske

Electrically evoked somatosensory potentials can be recorded by surface electrodes at several locations along the somatosensory pathway: peripheral nerve,[1-3] spinal cord,[4-8] brainstem,[6-8] and somatosensory cortex.[9-11] The neural generators of these potentials have been studied in animals.[12,13]

Potentials evoked by mechanical cutaneous stimuli (e.g., tapping on body surfaces) hold the promise of examining the activity along the full length of the human somatosensory pathway, from receptor to cortex, in response to a "natural" cutaneous input, without the discomfort often associated with electrical stimulation. Studies of mechanically evoked potentials have been limited to peripheral nerves[14-16] and to components that are probably generated in the cerebral cortex.[17-20] Recently, we described procedures for recording mechanically evoked potentials from additional levels of the somatosensory pathway.[21]

In the present study we compared potentials evoked by mechanical cutaneous stimulation with potentials evoked by electrical stimulation of nerves.

Methods. The subjects were 23 adults, 18 to 68 years old, without neurologic disease. They rested on a bed in a sound-attenuating chamber, with the left hand supported on a warmed plastic mold. Digital skin temperature was monitored continuously and was maintained between 33 and 36° C. The evoked potentials from each subject were collected in a single session in response to: (1) electrical stimulation of a digital nerve, (2) electrical stimulation of the median nerve at the wrist, and (3) mechanical stimulation of the fingernail. All stimuli were delivered at a rate of 4 per second. The recording session lasted 3 to 4 hours, during which time the subjects usually fell asleep.

The electrical stimuli were 0.2-msec-duration square-wave pulses of constant current, delivered to the digital nerve through ring electrodes around the middle and proximal phalanges of the index finger, or to the median nerve through silver cup electrodes placed at the wrist 3 to 4 cm apart and parallel to the median nerve. The proximal electrode of each pair was the cathode. The current was adjusted to a level just below that producing discomfort or a muscle twitch, whichever was lower.

The mechanical stimulus was produced by activating a moving coil vibrator with a 50-msec-duration electrical pulse. The sound produced by movement of the vibrator was masked by white noise from a speaker near the subject. Further details of the mechanical stimulus were provided elsewhere.[21]

From the Departments of Neurology and Pediatrics, University of California, Irvine.

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Requests for reprints should be addressed to Dr. Starr, Department of Neurology, University of California, Irvine, California College of Medicine, 101 City Drive South, Orange, CA 92668.

Digital nerve potentials were recorded from the ring electrodes on the digit (figure 1). The other recording electrodes were 9-mm-diameter silver cups attached to the skin by collodion glue, with resistance less than 3 kOhm. Recordings were obtained from appropriately placed surface electrodes over the peripheral nerve at the wrist, near the axilla, and over the brachial plexus (Erb's point). Spinal cord activity was recorded from an electrode placed over the second cervical vertebra (C2) referenced to the middle of the forehead (Fpz). Cortical activity was recorded from a scalp electrode at C4 (according to the 10-20 system) referenced to Fpz. When the electrode at C4 was referenced to the contralateral Erb's point electrode, components reflecting activity from peripheral nerve, spinal cord, subcortical somatosensory pathway, and cortex could be simultaneously detected.

The potentials were amplified with a gain of 200,000 using a band pass of 30 to 3000 Hz (3 dB down points, 6 dB/octave slope). The potentials evoked over a 51-msec period in response to 1000 stimuli were averaged by a four-channel averager using a dwell time of 200 μsec and 256 addresses per channel. A duplicate of each average was made to assess reproducibility. The average potentials were plotted, with positivity at grid 1 as an upward deflection, and stored on magnetic tape for further analysis. Latencies of various components of the recorded potentials were determined from the computer CRT screen with a cursor. Latencies were measured from the onset of the electrical pulse delivered to the peripheral nerves or to the mechanical vibrator.

Nerve conduction velocities along the peripheral nerve were determined by measuring the distance between the initial electrode at each site that recorded the propagated volley, and then dividing this distance by the latency difference between the negative peak of the potentials recorded at the two placements. The propagated action potential was assumed to be under the cathode of a stimulating electrode pair at the instant of stimulation. To evaluate the most distal portion of the nerve, the latency of the potentials evoked at the wrist by electrical stimulation of the digital nerve was subtracted from the latency of the mechanically evoked potentials, also recorded at the wrist. Thus, a measure of nerve ending function was obtained: nerve fiber and nerve ending conduction time (evoked mechanically) - nerve fiber conduction time (evoked electrically) = nerve ending conduction time. This measure was expressed in msec and was called Nerve Ending Conduction Time (NECT). NECT included, in addition, the activation time of the vibrator and the duration of coupling between the vibrator and the stimulated tissue, but these times were the same across subjects.

Measures of intercomponent conduction times were derived from the latency differences between the components recorded over: (1) brachial plexus and cortical hand area, (2) brachial plexus and cervical cord, and (3) cervical cord and cortical hand area.

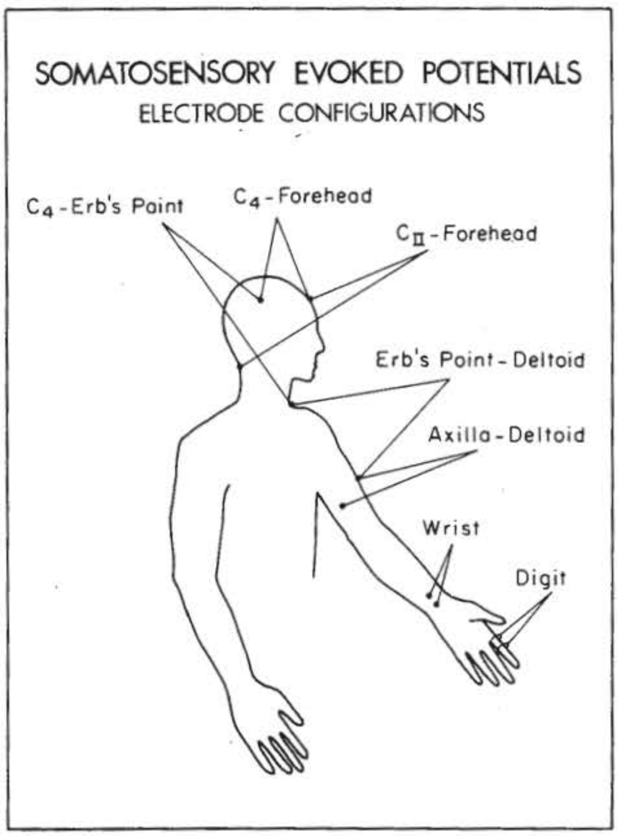

Figure 1. Electrode locations and recording configurations used in this study.

Results. Results were described in terms of the presumed site of origin of the potentials along the somatosensory pathway. The components were designated by polarity at grid 1 (P or N) and average latency in msec (figure 2).

Median nerve. Mechanically evoked potentials recorded by the digital electrodes were primarily an artifact of movement.[21] In contrast, potentials evoked by electrical stimulation at the wrist and recorded by the digital electrodes consisted of a biphasic, short-duration component (N3-P4), followed by a broader monophasic component (P9). P9 only accompanied high-intensity electrical stimulation that produced muscle twitches. An electromyogram (EMG) recorded by surface electrodes over the thenar muscle had a latency comparable to P9, and appeared with the same threshold of stimulus intensity. In contrast, N3-P4 occurred prior to any muscle activity, assuring its neural origin.

The electrode overlying the median nerve at the

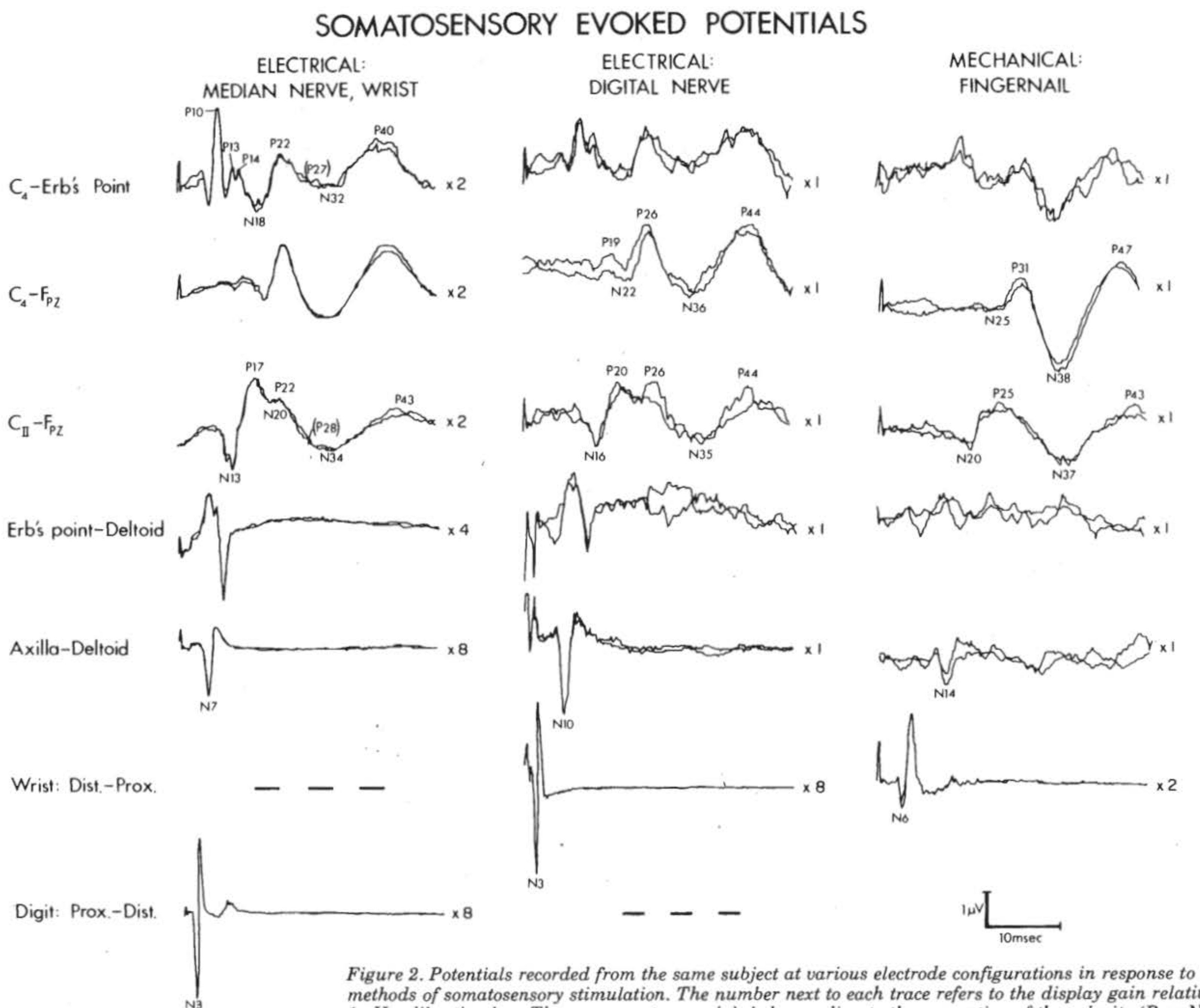

Figure 2. Potentials recorded from the same subject at various electrode configurations in response to three methods of somatosensory stimulation. The number next to each trace refers to the display gain relative to the 1-μV calibration bar. The components were labeled according to the convention of the polarity (P or N) at grid 1 of the differential recording pair, followed by the average latency rounded to the nearest msec.

wrist recorded biphasic activity in response to either mechanical or electrical stimulation of the digit. The relative amplitudes of the positive and negative components of the whole-nerve action potential depended on the relative proximity of the proximal and distal recording electrodes to the nerve trunk, making measures of absolute amplitudes very variable. However, in each subject, the ratio of both the amplitude and the duration of the median nerve potentials evoked by electrical stimulation of the digital nerve could be compared to the potentials evoked by mechanical stimulation. Potentials evoked by electrical stimulation were of both higher amplitude (10/1) and shorter duration (2/3) than those evoked by mechanical stimulation (figure 2).

Electrodes overlying the proximal portion of the median nerve near the axilla recorded activity evoked by the three stimuli that was similar in shape and consisted of a major negative peak preceded and followed by smaller positive peaks. The negative peak evoked by electrical stimulation was considerably larger than the one evoked mechanically (14/1 for electrical stimulation at the wrist and 3/1 for electrical stimulation of the digital nerve). The durations of the negative peaks evoked by all three methods of stimulation were comparable (approximately 4 msec). Because the median nerve potentials evoked at the wrist by electrical stimulation of the digital nerve had a shorter duration than those evoked by mechanical stimulation, the finding of comparable durations near the axilla indicates that the mechanically evoked potentials had considerably less temporal dispersion than electrically evoked potentials in propagating from wrist to axilla.

Brachial plexus. The electrode overlying the brachial plexus at Erb's point referenced to an electrode over the deltoid insertion recorded clear potentials in response to the electrical stimuli, consisting of a major negative peak preceded by a double positive peak. In contrast, potentials evoked by mechanical stimulation could not be identified in most subjects because of poor signal-to-noise ratio.[21]

Upper neck. Potentials recorded over the neck at C2 referenced to Fpz had a similar shape and duration in response to all three methods of stimulation: an initial negative peak followed by a positive component, typically consisting of two peaks. The two peaks in the mechanically evoked potentials (P23 and P29) blended into a single broad component (P25). The negative peaks recorded from the upper cervical region in response to electrical stimulation were larger than peaks recorded after mechanical stimulation (3.5/1 for electrical stimulation of the median nerve at the wrist and 1.8/1 for electrical stimulation of the digital nerve), but were of comparable duration. The ratio of the amplitudes of the initial negativity recorded over the neck compared to the amplitude of the potentials recorded in the same subject over the proximal median nerve near the axilla (neck/axilla) was 0.15 ± 0.06 for electrical stimulation of the median nerve at the wrist, 0.46 ± 0.23 for electrical stimulation of digital nerve, and 0.73 ± 0.32 for mechanical stimulation of the fingernail. Because potentials recorded from axilla and neck were of comparable duration for the three types of stimulation, the amplitude ratio differences indicated that fewer fibers, relative to the number of peripheral nerve fibers, contributed to the cervical potentials, when evoked by electrical stimulation (particularly of the median nerve at the wrist) than when evoked after mechanical stimulation.

Cortex. The cortical potentials recorded from the C4-Fpz electrodes were essentially similar in shape and duration for the three types of stimuli, with an initial negative peak followed by two prominent positive peaks. These prominent peaks corresponded in latency to the C2-Fpz recorded potentials following the initial negative and positive peaks. For example, in the potentials evoked by electrical stimulation of the digital nerve, P26 and P43 recorded by C4-Fpz correspond to P26 and P44 recorded by C2-Fpz. In approximately half the subjects, the first prominent positivity evoked by electrical stimulation at the wrist (P22) was followed by an additional component (P27) corresponding in latency to a component (P28) recorded by C2-Fpz. In contrast to potentials recorded at other sites, cortical potentials evoked by the three methods of stimulation were of comparable amplitudes.

Cerebral-brachial plexus derivation (C4-Erb's point). A spectrum of the variations of the potentials recorded with this configuration, in response to the three somatosensory stimuli employed, is given in figure 3. The potentials evoked by electrical stimulation had an initial prominent peak (P10 for stimulation at the wrist and P12 for digital stimulation) corresponding in latency to potentials recorded at the brachial plexus, but opposite in direction because in the two recording montages Erb's point potentials were channeled to opposite grids. This component was followed after 3 to 4 msec by a positive-negative complex corresponding in latency but inverted when compared to the potentials recorded over the spinal cord. After electrical stimulation of the nerve at the wrist, this component (P13) was typically followed by an additional component (P14). A final set of positive-negative-positive components (occurring 9 to 13 msec later) corresponded in latency and direction to the cortical events recorded by C4-Fpz. Potentials evoked by mechanical stimulation had a poorly reproducible component (P17) corresponding in latency to the activity at Erb's point, followed by a component at the same latency as the upper neck potentials. The subsequent component

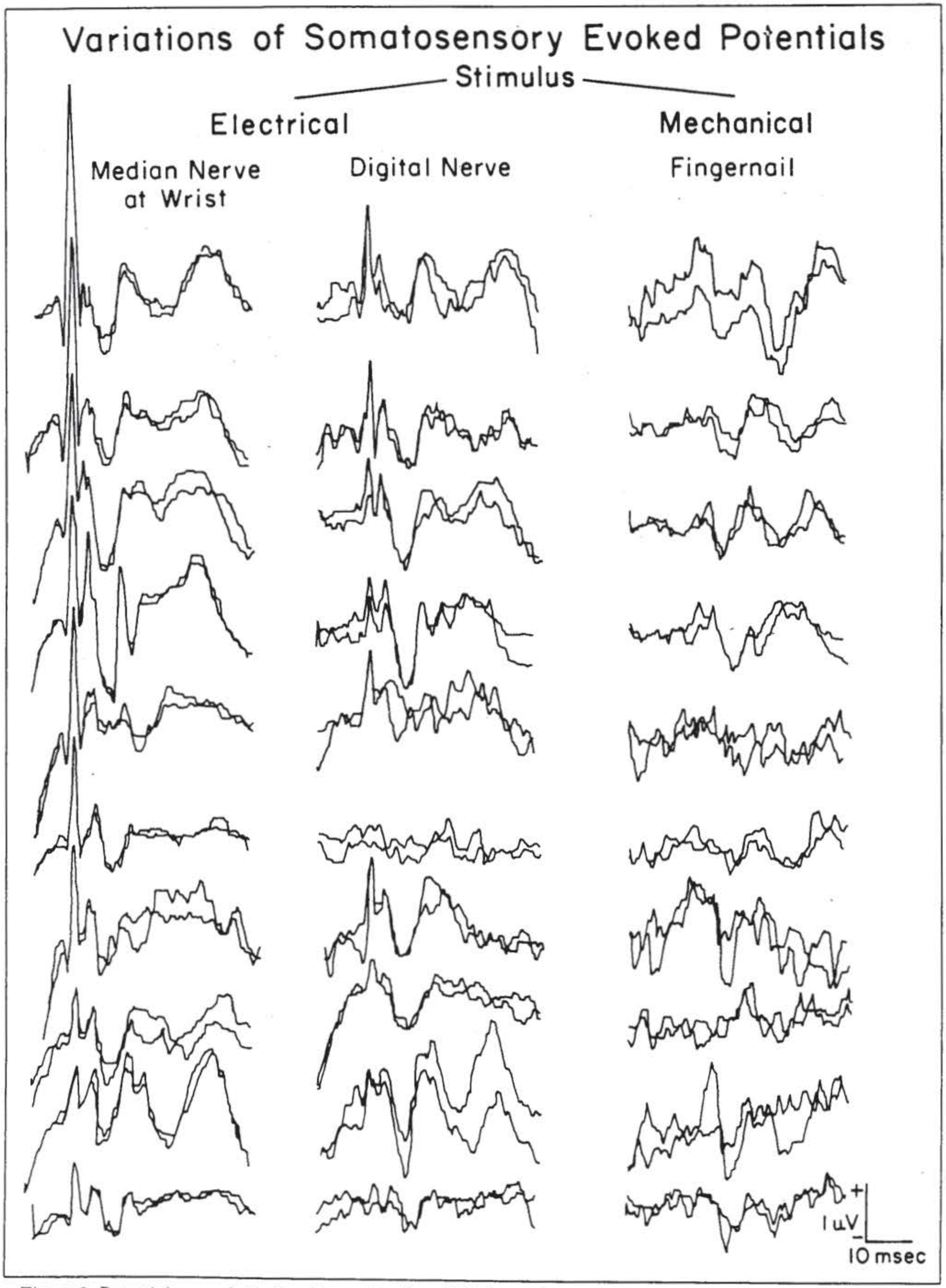

Figure 3. Potentials recorded using the cerebral-brachial plexus derivation in response to the three methods of somatosensory stimulation. The potentials in each line are from the same subject. The initial component recorded over the brachial plexus was aligned in the electrically evoked potentials to facilitate comparison. The 10 subjects represent the full range of variations of waveforms encountered among the 23 subjects. The amplitude calibration bar is 2 μV for the potentials evoked by electrical stimulation of median nerve at the wrist, and 1 μV for the other potentials.

Table 1. Components of somatosensory evoked potentials

Digit: proximal-distal						
Stimulus: (md)	NR					
(ed)	NR					
(ew)	N 3.2 ± 0.2 15.5 ± 11.4					
Wrist: distal-proximal						
Stimulus: (md)	N 6.2 ± 0.8 1.5 ± 0.7					
(ed)	N 3.2 ± 0.3 14.9 ± 7.0					
(ew)	NR					
Axilla-Deltoid						
Stimulus: (md)	N13.8 ± 1.4 0.7 ± 0.3					
(ew)	N 9.6 ± 0.8 1.8 ± 0.9					
(ed)	N 6.8 ± 0.6 9.9 ± 4.0					
C2-Fpz						
Stimulus: (md)		N20.4 ± 2.0 0.4 ± 0.2		P25.4 ± 2.0 1.1 ± 0.3	N36.6 ± 2.8	P42.8 ± 4.6
(ed)		N16.2 ± 1.4 0.7 ± 0.3	P20.2 ± 1.6 0.7 ± 0.4	P25.6 ± 2.3 1.0 ± 0.5	N35.4 ± 3.0	P43.7 ± 3.0
(ew)*		N13.2 ± 0.8 1.4 ± 0.7	P16.8 ± 1.0 1.4 ± 0.5	P22.2 ± 2.2 0.9 ± 0.5	N33.5 ± 2.3	P43.0 ± 3.4
C4-Fpz						
Stimulus: (md)			N25.2 ± 3.4 1.3 ± 0.6	P30.6 ± 3.4	N37.7 ± 3.8	P46.7 ± 2.2
(ed)		P18.8 ± 1.4 0.5 ± 0.3	N22.1 ± 1.6	P26.4 ± 2.4 1.5 ± 0.9	N35.7 ± 2.7	P43.5 ± 3.4
C4-Erb's point						
Stimulus: (ew)†	P10.0 ± 0.6 3.8 ± 2.2	P13.2 ± 1.0 0.4 ± 0.5	N17.7 ± 1.3	P22.0 ± 1.8 0.9 ± 1.0	N31.6 ± 2.2	P40.5 ± 1.7
		P14.2 ± 0.8 2.5 ± 0.8				

NR Not recorded
* An additional component, P28.2 ± 1.4, was found in 12 of the subjects.
† An additional component, P27.2 ± 2.4, was found in 13 of the subjects.

Average values of latency (msec, top line of each pair of entries) and amplitude (μV, bottom line of each pair of entries), with standard deviations from all 23 subjects. Amplitudes were measured from the baseline or preceding positive peak (if present) to the negative trough. No amplitude measures were determined for components with a latency larger than 30 msec. Values for P14, recorded using the C4-Erb's point derivation, are listed immediately below the values for P13. The components listed are labeled in the traces of figure 2. The stimuli used were: (md) mechanical stimulation of the fingernail, (ed) electrical stimulation of digital nerves, and (ew) electrical stimulation of the nerve at the wrist.

Table 2. Median nerve conduction velocity (m/sec)

	Digit to wrist (ed)	Wrist to digit (ew)	Wrist to axilla (ed)	Wrist to axilla (ew)	Wrist to axilla (md)
Average	50.1	52.6	61.1	59.4	57.8
−2 SD	42.3	47.2	54.9	52.8	47.6
−3 SD	38.4	44.5	51.8	49.5	42.5

Average values of nerve conduction velocities with lower limits (2 and 3 standard deviations below average) for two portions of the median nerve, in response to three methods of somatosensory stimulation. The letters in parenthesis indicate the stimulus used: (ed) electrical stimulation of digital nerves, (ew) electrical stimulation of the nerve at the wrist, (md) mechanical stimulation of the fingernail.

was identical to the one recorded with C4-Fpz.

Tables 1 to 3 contain quantitative measures of the somatosensory evoked potentials.

Discussion. These results show that comparable potentials can be recorded along the somatosensory pathway in response to either mechanical stimulation of the fingernail or electrical stimulation of the nerves innervating the hand. In general, mechanically evoked potentials were of lower amplitude and contained fewer components than the electrically evoked events, suggesting that the electrical stimulus activated more fibers more synchronously than did the mechanical stimulus. In contrast, temporal dispersion of the potentials evoked by mechanical stimulation was less than in the electrically evoked events during conduction along the median nerve, suggesting that the mechanically evoked potentials originated from a relatively uniform fiber population. The comparatively long duration of mechanically evoked potentials recorded from the median nerve at the wrist was probably due to coupling of the stimulus to the skin and underlying tissues.

Although the potentials recorded from the electrodes overlying the digital nerve in response to mechanical stimulation of the fingernail were primarily an artifact of movement,[21] we believe that nerve ending conduction time (NECT), derived from measures of the potentials recorded at the wrist in response to electrical stimulation of the digital nerve and mechanical stimulation of the fingernail, provides the information necessary for distinguishing receptor and nerve-ending impairments.

The nerve conduction velocities obtained by measuring peak latency differences reflected modal velocity of conduction in the nerve. The peripheral nerve conduction velocities for the distal portion of the nerve were slower than for the proximal portion of the nerve (table 2), perhaps because of the small diameter of the nerve fibers in the distal nerve.[22,23]

The measurement of the change in amplitude of

Table 3. Somatosensory conduction times (msec)

	NECT	Plexus to cord (ew)	Plexus to cortex (ew)	Cord to cortex (ew)	Cord to cortex (ed)	Cord to cortex (md)
Average	3.6	3.2	12.0	9.0	9.8	10.2
+2 SD	4.7	4.2	13.6	10.8	12.8	14.0
+3 SD	5.2	4.7	14.4	11.7	14.3	15.9

Average values of latency differences (conduction times) with upper limits (2 and 3 standard deviations above average). NECT denotes Nerve Ending Conduction Time (fingernail to digit; see Methods section). The letters in parentheses indicate the stimulus used to evoke the potentials measured: (ed) electrical stimulation of digital nerves, (ew) electrical stimulation of the nerve trunk at the wrist, (md) mechanical stimulation of the fingernail.

the potentials evoked along the median nerve and spinal cord provides additional information about the fibers activated by the three types of stimuli. Judging from the changes in the amplitude ratios of the potentials recorded over the spinal cord and those recorded over the median nerve near the axilla (neck/axilla), many fibers activated by electrical stimulation of the median nerve at the wrist were probably antidromically conducting motor fibers. Motor fibers do not propagate along the ascending pathways of the spinal cord after synapses in the anterior horn, so that the relative amplitude decreases at the spinal level. Furthermore, the amplitude ratios indicated that the neural population recorded in response to electrical stimulation of the digital nerve was also more diverse than after mechanical stimulation. The asynchronous arrival of action potentials at the spinal level, caused by the temporal dispersion along the peripheral nerve, may have resulted in further loss of synchrony past synapses and contributed to the relatively reduced amplitude of the electrically evoked cervical potentials.

In contrast, all three stimuli evoked cortical potentials of comparable amplitude. This is a paradox, since the number and types of nerve fibers activated by the various stimuli are very different. Among the possible explanations for this phenomenon is the divergence of electrically activated pathways to subcortical levels, with fewer fibers reaching the cortex, giving rise to the relative amplitude loss of the cortical electrically evoked potentials. Further desynchronization as a result of additional synapses between spinal cord and cortex may also have contributed to the lower amplitude of electrically evoked cortical potentials.

There were two differences in morphology between the potentials evoked by electrical stimulation at the wrist and the potentials evoked by the other two methods. First, electrical stimulation at the wrist evoked an additional cortical component (P27) in half the subjects. Second, with the widely spaced electrodes (C4-Erb's point) there was an additional component (P14) in response to electrical stimulation at the wrist, not present with the other methods. P14 may arise from a generator between the upper cervical cord and the cortex, possibly in the brainstem.[6-8] A thalamic contribution to this component cannot be excluded because depth recordings from the human thalamus gave potentials at latencies corresponding to both this minor positive peak and the following negative peak.[13,24-29] The differences between the potentials recorded in response to the different stimuli may reflect differences in the fiber pathways activated, or in their number and degree of synchrony resulting from the stimuli used.

The finding of comparable potentials from peripheral nerve to cortex in response to electrical stimulation of a mixed nerve (the median nerve at the wrist), a sensory nerve (the digital nerve), and the receptor surface by mechanical means provides the clinical neurophysiologist with a combination of methods to quantify somatosensory function in patients. Each method of stimulation has particular advantages. For instance, electrical stimulation is easy to apply and evokes relatively large-amplitude components. However, electrical stimulation may be painful, and there is uncertainty as to the type and number of fibers activated. Mechanical stimulation of the finger can be done without any discomfort and provides information about a specific group of receptors and their nerve pathways. However, the coupling of the mechanical stimulus to the skin surface requires fixing the finger and relatively complex methods for quantifying the displacement, force, and velocity of the stimulus. Nevertheless, a combination of these methods can be applied to the numerous clinical problems of somatic sensation that accompany neurologic disorders, to assist in the localization and definition of the mechanisms of the sensory impairment.

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