Comparison of algorithms of testing for use in automated evaluation of sensation

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Article abstract—Estimates of vibratory detection threshold may be used to detect, characterize, and follow the course of sensory abnormality in neurologic disease. The approach is especially useful in epidemiologic and controlled clinical trials. We studied which algorithm of testing and finding threshold should be used in automatic systems by comparing among algorithms and stimulus conditions for the index finger of healthy subjects and for the great toe of patients with mild neuropathy. Appearance thresholds obtained by linear ramps increasing at a rate less than 4.15 μm/sec provided accurate and repeatable thresholds compared with thresholds obtained by forced-choice testing. These rates would be acceptable if only sensitive sites were studied, but they were too slow for use in automatic testing of insensitive parts. Appearance thresholds obtained by fast linear rates (4.15 or 16.6 μm/sec) overestimated threshold, especially for sensitive parts. Use of the mean of appearance and disappearance thresholds, with the stimulus increasing exponentially at rates of 0.5 or 1.0 just noticeable difference (JND) units per second, and interspersion of null stimuli, Békésy with null stimuli, provided accurate, repeatable, and fast estimates of threshold for sensitive parts. Despite the good performance of Békésy testing, we prefer forced choice for evaluation of the sensation of patients with neuropathy.

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Estimates of detection thresholds for various modalities of sensation may be used to (1) study normal sensation; (2) estimate normal values by modality and for site, age, sex, and other variables; (3) follow the course of sensory loss in neurologic disease; (4) detect selective modality sensory loss, which is useful in differential diagnosis; (5) detect altered or changed threshold for the conduct of controlled clinical or epidemiologic trials; and (6) compare with electrophysiologic, pharmacologic, or morphometric alteration of biopsy specimens of nerves.[1] Modalities of sensation commonly tested are touch pressure, vibration, cool, warm, pain, and other sensations. Elevated sensory thresholds in peripheral neuropathy, assuming that they have been adequately evaluated, provide more direct evidence of a clinical abnormality than do such surrogate measures as nerve conduction.[2-6] Increased cool detection threshold (CDT) or warm detection thresholds (WDTs) provide evidence of involvement of small fibers not adequately monitored by the EMG examination. For investigational characterization and longitudinal follow-up of diabetic neuropathy patients, the San Antonio consensus panel recommended use of quantitative sensory examination (QSE), clinical assessment of neuropathic symptoms, deficits, nerve conduction and EMG abnormalities, and quantitative autonomic examination.[7]

To achieve sensitive, specific, and repeatable QSE results, considerable attention needs to be given to (1) the conditions of the subject or patient and of the testing environment, (2) the characteristics and waveform of the stimulus, (3) the algorithm of testing and finding threshold, and (4) the number and appropriateness of controls (considering test, site, age, sex, and other variables).

Microprocessor-controlled systems can now be designed and used that deliver appropriate, quantitated, and graded stimuli over a wide range of intensities. They use sophisticated algorithms of testing and finding threshold and provide results specific for modality, site, age, and sex.[8] Because these systems are automated, they can be operated by technicians as well as by physicians, and may provide a cost-effective test because the initial high cost is offset by the improved performance and the decreased cost of use of physician time. These systems also have considerable advantages over sensory tests that are given in different ways and by different professionals in that the responses should not vary even when the test is administered differently.

The present studies examined the effect of use of 3 different methods of programmed testing (algorithms) on vibratory detection threshold (VDT) in healthy subjects and in patients with mild neuropathy: (1) a forced-choice algorithm that used 25 discrete magnitudes of stimulation, (2) a linear ramp algorithm with null stimuli, and (3) a modified Békésy algorithm with null stimuli. For the latter 2 algorithms, secondary issues explored were the influence on VDT of the rate and kind of increase of stimulus amplitude, number of stimuli used, and use of cueing lights. These studies were performed with a newly designed computer-assisted sen-

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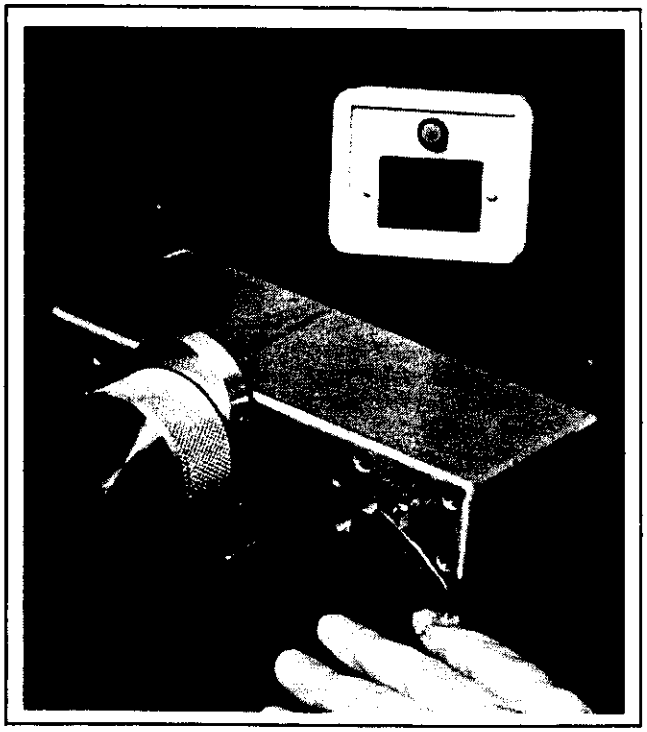

Figure 1. The tone-arm and vibratory stimulus transducer used in computer-assisted sensory examination (CASE IV).

sory examination (CASE IV) system, designed to test VDT, CDT, and WDT. (CASE IV can be obtained from W.R. Medical Electronics, 123 North 2nd St., Hastings, MN 55082.) Here we describe only the components and results related to testing VDT. Thresholds obtained by these different algorithms were compared for accuracy, repeatability, and speed of testing.

Methods. *CASE IV system.* The system was designed to determine VDT for assessing large-diameter sensory fiber function and CDT and WDT for assessing small-diameter sensory fiber function.

The system consists of (1) a personal computer, hard and floppy disks, and a keyboard for entry of biographic data, selection of testing format, setting test conditions, administration of the algorithm of testing, estimation of threshold, comparison of threshold to that of controls, and generation of test results; (2) a videoscreen for display of program instructions, testing options, error messages, and results; (3) an electronic controller (containing power supplies, fail-safe devices and microprocessors, and circuitry) to provide discrete levels of stimulus intensity for forced-choice testing and linear and exponential increases of stimulus magnitude for the 2 other algorithms of testing; (4) a printer (of biographic information and results); (5) a visual cueing device (to display the "get ready" yellow light and "test in progress" green light, and for display of the numbers 1 and 2 for alternative forced-choice testing); (6) an observer or patient response key to indicate "appearance" threshold in the linear ramp algorithm with null stimuli testing, appearance and disappearance thresholds in the Békésy algorithm with null stimuli testing, and the choice of 1 or 2 in forced-choice testing; and (7) a vibratory transducer assembly and a thermode assembly. The software for operation of the system was written in C language.

Vibratory transducer. The stimulating disk making contact with the skin was 9 mm in diameter, had beveled edges, and was coated with Teflon (to reduce heat loss to the skin). The disk was mounted by a shaft to an optical scanning motor (G 302 series, General Scanning, Watertown, MA) with vertical displacement proportional to current (figure 1). The motor and probe were affixed to the front end of a balance arm with sufficient mass so that it would not respond to the rapid sinusoidal oscillations at 125 Hz but would move up or down with the slow motion of the anatomic part being tested. The stimulating disk rested on the finger, toe, or other part to be tested, with a load of 30 grams.

Forced-choice algorithm of testing. Twenty-five discrete levels of vibratory stimulation were used, ranging from 0.07 to 1,200 μm of displacement. The magnitude of the 25 levels of stimulus intensity was distributed from smallest to largest intensity by using an exponential function based on our previous study[8] of just noticeable difference (JND). Each level of stimulation therefore corresponds to 1 JND unit. The rise and fall of the vibratory stimulus at 125 Hz from 0 to each of the discrete levels of the stimulus intensity being tested had the characteristics of a charging and discharging capacitor (figure 2). The rules of testing were based on our previously published algorithm[9] and on recent modifications. In brief, a vibratory stimulus at a given level of intensity was presented during only 1 of a pair of stimulus events indicated to the patient by the serial display of the numbers 1 and then 2. Whether the stimulus was given in 1 or 2 was by chance. By depressing a response key, the subject indicated the interval that contained the vibratory stimulus. Success or failure at this level resulted in the subsequent test being given at lesser or greater stimulus intensities, respectively. Success was defined as correct identification of the stimulus interval in a pair of stimulus events 6 of 7 times, or 5 of the 1st 6 times, the 7th time incorrect, and the 8th and 9th time correct. Testing was begun at level 13 with subsequent stepping to larger or smaller levels in increments of 4, 4, 2, 2, 1, 1, 1, 1, preceding turnarounds 1 through 8 respectively. This sequence was altered so that single stepping to smaller levels occurred after the 1st failure (figure 3). The threshold was the median of the last 6 turnaround values. A typical sequence is shown in figure 3.

Linear ramp algorithm with or without null stimuli and with or without cueing lights. Unlike the forced-choice algorithm, the stimulus magnitude increased linearly at ramp rates that were specified (0 to 16.6 μm/sec), and from 0 to the point at which the response key was depressed or to a maximal stimulus of 1,200 μm. A typical stimulus and testing sequence is shown in figure 2.

In the test situation, the operator chose the test (VDT, WDT, or CDT), the algorithm to be used, the number of stimuli and null stimuli to be used, and whether cueing lights ("get ready" and "test in progress") would be used. Typically, in the studies reported here, threshold was based on the mean result of 8 or 12 stimuli and 4 null stimuli randomly dispersed among the stimuli after the 1st stimulus. Tests were done with and without cueing lights. The duration of null stimuli was the mean duration of preceding stimuli.

In a typical test the stylus rested on the dorsum of the distal phalanx of index finger or great toe just proximal to the nail. The subject was instructed to depress the response key just as soon as vibration was felt. Only appearance thresholds (A, in figure 2) were evaluated. Ramp rates tested were 0.08, 0.17, 0.83, 4.15, and 16.6 μm/sec.

Békésy algorithm with null stimuli. In this algorithm, a modification of the Békésy approach for assessing auditory thresholds, both appearance and disappearance thresholds were signaled. The continuous rate of increase or decrease followed our estimate of JND (an exponential function, not

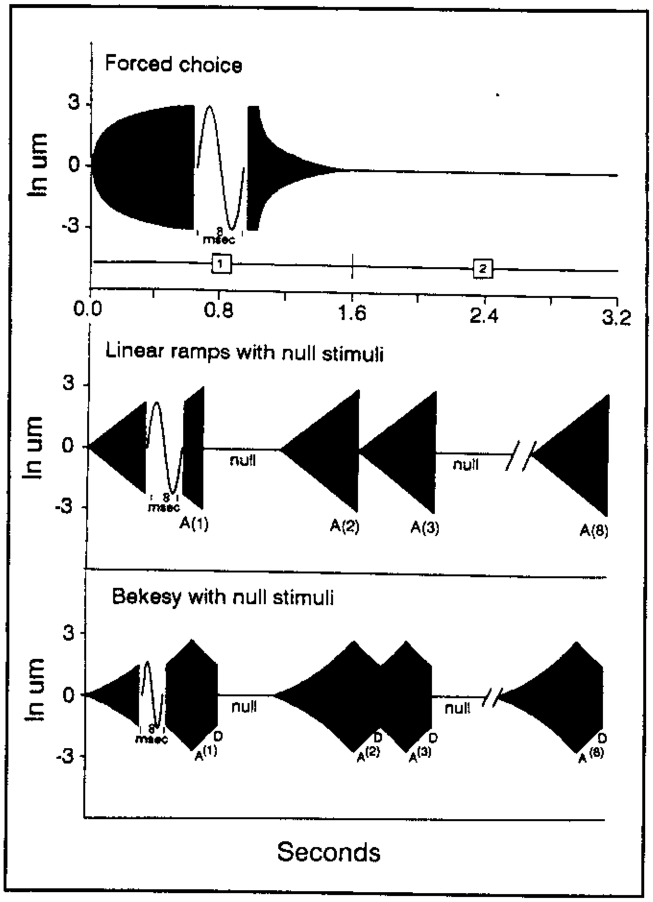

Figure 2. Shown here are the waveforms used in forced-choice testing (upper), linear ramps with null stimulus (middle), and Békésy with null stimuli (lower). Although sinusoidal waveforms at 125 Hz are used for all 3 algorithms, the rate and shape of the increase of intensity and the method of testing are different among algorithms. In alternative forced-choice testing, the observer is asked to choose the interval, associated with the display of the number 1 and then 2, that had a vibratory stimulus. The rules of testing and finding threshold are described in text. In linear ramp testing with null stimuli (middle), the intensity of vibratory stimuli increases to the point at which the response key is depressed. After the initial stimulus, 7 stimuli and 4 null stimuli are presented as described in text. A(1), A(2), A(3), and A(8) indicate the 1st, 2nd, 3rd, and 8th appearance thresholds in a typical sequence. Null stimuli are shown as "null." In Békésy testing with null stimuli (lower), the rate of increase of the vibratory stimulus follows an exponential function based on our previous study of just noticeable difference. The A(1)D, A(2)D, A(3)D, and A(8)D refer to the 1st, 2nd, 3rd, and 8th "appearance" and "disappearance" thresholds. Null stimuli are indicated by the word "null."

log 10 function as it is in audiometric testing).

The waveform, exponential increase and decrease of vibratory stimuli at 125 Hz, and random assignment of null stimuli among 8 stimuli are shown in figure 2. In addition, null stimuli had been interspersed among stimuli from a bank of random numbers so that stimulus events could not be predicted. In the experiments done here, rates of 0.5, 1, or 2 JND/sec were used. Typically, 8 stimuli and 4 null stimuli were presented. In this algorithm, appearance and disappearance thresholds were signaled by depressing and releasing the response key. The VDT was the mean of the appearance (A) and disappearance (D) thresholds for 8 stimuli. If the response key was depressed during a null stimulus, the test was automatically stopped and a message was displayed on the videoscreen, instructing the observer to reinstruct the patient and to rerun the test.

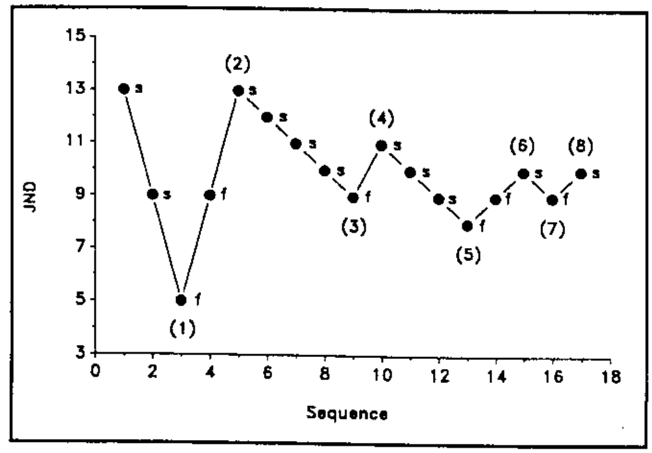

Figure 3. A typical sequence of testing with the forced-choice algorithm. The abbreviated rules by which the stimulus increases or decreases and the method of calculating the threshold are given in text. JND = just noticeable difference, s = success, and f = failure. The numbers in parentheses indicate the turnarounds.

Instruction of subjects or patients. The sensory technician read a specially prepared statement to minimize instruction differences. The instructions differed depending on the algorithm used. Subjects or patients were told that the object of the test was to determine the smallest vibratory stimulus that could be felt. They were told that they might experience the vibratory stimuli as "vibration," "buzzing," "trembling," or "rumbling."

In forced-choice testing, subjects were told that they must indicate by depressing the response key 1 or 2, or by saying 1 or 2 (when the observer depressed the response key for the patient) whether or not they felt vibration during the display of the number 1 or 2. If they had difficulty knowing (or did not know) in which stimulus interval the stimulus had occurred, they still had to choose an interval "most likely" to have included the stimulus. The word "guessing" was avoided. They also were told that a stimulus was always given during the display of either number 1 or 2 but never both 1 and 2. They were also told that if they became distracted or drowsy so that they could not concentrate, they should so indicate to the observer so that the test could be stopped. A short demonstration was provided and questions were answered before beginning the formal test.

For linear ramp testing, subjects were asked to depress the response key just as soon as they felt the vibration. They were also told that there would be pauses when no stimuli were given and that if the button was depressed during these times, the test would be stopped automatically. The number of stimuli and null stimuli to be used was not indicated.

In Békésy testing, subjects were told that the response key should be depressed just as soon as the vibration was felt and should be kept depressed until the stimulus was no longer felt. They were told that null stimuli were interspersed among stimuli, but the number of each was not given. Subjects and patients were told that if the response key was depressed during a null stimulus, the test would be stopped, and after

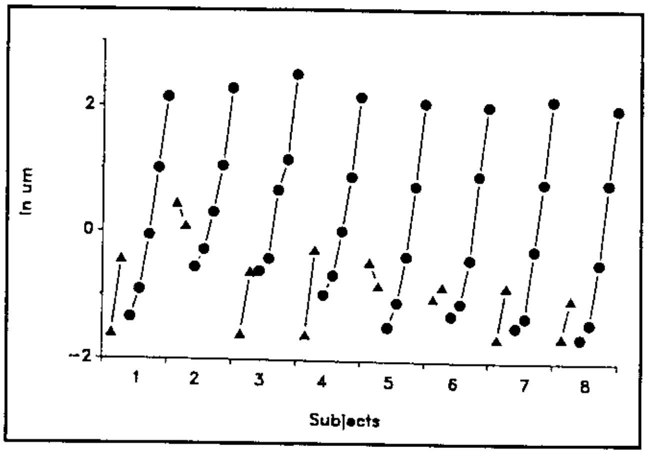

Figure 4. Vibratory detection threshold (VDT) for the index finger in 8 subjects from a forced-choice algorithm (triangles) and "appearance thresholds" from linear ramps (circles). The VDTs based on testing with the forced-choice algorithm were performed on separate days. The 1st threshold value is displayed to the left of the 2nd value. The thresholds from linear ramps at 0.08, 0.17, 0.83, 4.15, and 16.6 μm/sec are joined by lines from left to right for each of the 8 subjects. As described in text, the thresholds with slow linear ramps (0.08, 0.17, and possibly even 0.83 μm/sec) are comparable to those obtained from forced-choice testing. Slow ramps are not speedy enough for testing insensitive sites, making their use impractical in automated systems. Use of fast ramps clearly overestimated threshold. This overestimation probably results from the subject's inability to stop the stimulus quickly enough because of the reaction time.

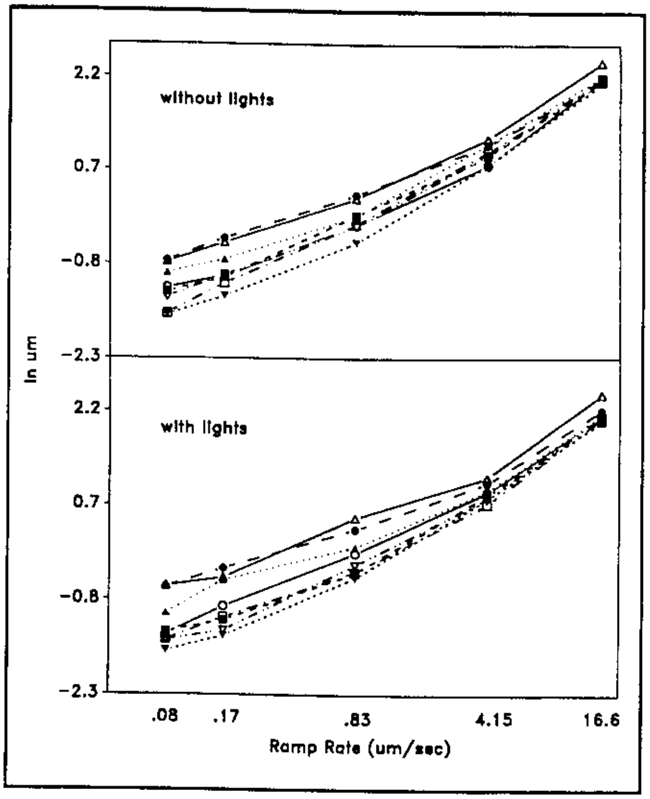

Figure 5. The "appearance thresholds" from use of the linear ramp with null stimuli algorithm for the index finger of 8 healthy subjects, as performed without cueing lights (above) and with cueing lights (below). For the algorithm with and without cueing lights, the threshold increased significantly with each increase of ramp rate. Cueing lights did not appear to affect the response. The different symbols represent different subjects.

instruction the test would have to be repeated.

Healthy subjects. Healthy subjects were recruited from laboratory workers and from Rochester volunteers. These subjects were not known to have neuropathy or disease known to predispose to neuropathy.

Neuropathic patients. Patients with mild neuropathy were recruited from patients referred to 1 of us (P.J.D.) and from the Rochester Diabetic Neuropathy Study (RDNS—a population-based prospective epidemiologic study of the prevalence, characteristics, and risk factors for staged severity of diabetic neuropathy in Rochester, MN).

Results. *VDT from different linear ramps compared with VDT from forced-choice algorithm.* The VDT for the left index finger increased progressively with use of increasing ramp rates of 0.08, 0.17, 0.83, 4.15, and 16.6 μm/sec for each of the 8 healthy subjects (figure 4). This same change occurred whether cueing lights were used or not (figure 5).

The VDTs from use of different ramp rates were compared with 2 estimates of VDT based on forced-choice testing (figure 4). The 2 lowest ramp rates (0.08 and 0.17 μm/sec) gave results similar to those obtained from forced-choice testing (figure 4). The 0.83 μm/sec ramp resulted in higher thresholds than either of the thresholds from forced-choice testing in 7 of 8 subjects. VDTs from use of 4.15 or 16.6 μm/sec linear ramps were markedly above thresholds from forced-choice testing in all cases.

An obvious explanation for why appearance thresholds using linear ramps might overestimate threshold came from the experience of subjects and from a consideration of the influence of reaction times on VDT when ramp rates are high. Assuming a reaction time of 100 msec (sensory transduction, relay and decision making, and motor reaction—an approximate estimate), the difference between thresholds at different ramp rates is approximately accounted for.

Use of linear ramps and appearance threshold and low rates of increase of stimulus amplitude—eg, 0.17 μm/sec—might provide sufficient accuracy for assessing sensitive parts but would be too slow for assessing insensitive parts in an automated system. For an insensitive part for which it might be necessary to give a maximal stimulus (1,200 μm), it would require approximately 118 minutes, using a linear ramp of 0.17 μm/sec, to test 1 stimulus ramp—clearly an unacceptable time.

In view of these results, 3 strategies to improve performance (already used extensively in audiology) were explored: (1) use of mean appearance and disappearance thresholds with fast ramps; (2) use of stimuli whose amplitude increased exponentially; and (3) a combination of 2 and 3 (see subsequent sections).

Effect of different numbers of stimuli on "appearance" VDT. The appearance VDT was estimated for the distal phalanx of the index finger in 8 healthy sub-

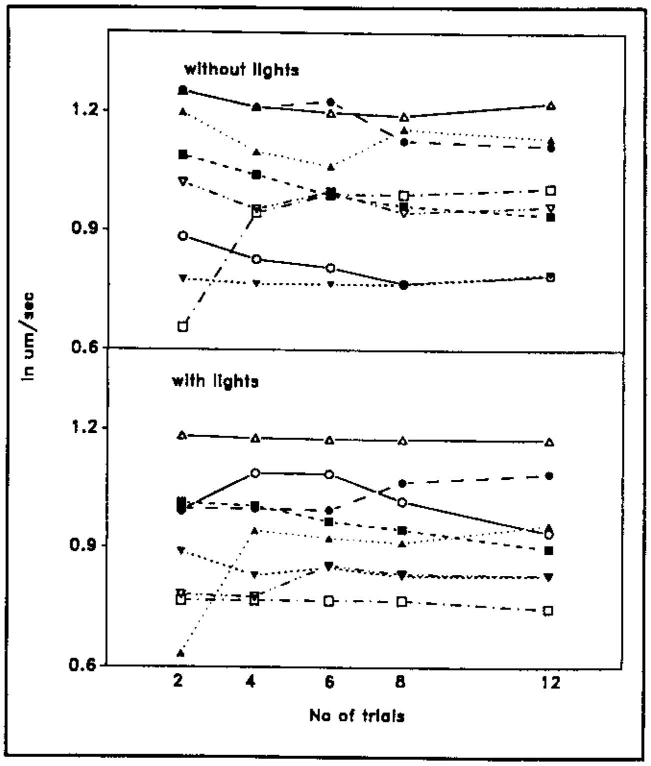

Figure 6. The "appearance thresholds" based on an evaluation of the first 2, 4, 6, 10, and 12 linear ramps with null stimuli increasing at a rate of 4.15 µm/sec. Four or more stimuli appeared to provide a reasonably good estimate of threshold based on 12 trials. The different symbols represent different subjects.

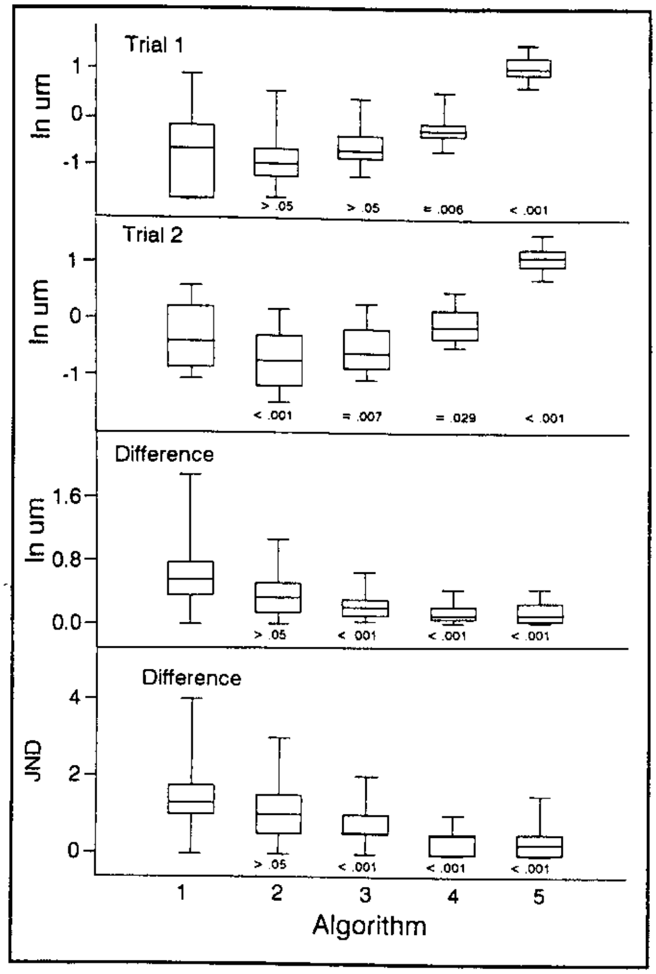

Figure 7. The distribution of vibratory detection thresholds (VDTs) for the index finger of 20 healthy subjects on 2 occasions (trials 1 and 2) and the difference in thresholds between the 2 shown as ln um and as JND by using a forced-choice algorithm (1), Békésy testing with null stimuli (2 = 0.5 JND/sec, 3 = 1 JND/sec, and 4 = 2 JND/sec), and linear ramps with null stimuli (5 = 4.15 µm/sec). The box and whisker figures represent the extremes and the 25th, 50th, and 75th percentile values. By the criteria of obtaining the same result (repeatability) and accuracy, algorithms 2 and 3 performed well. Algorithms 4 and 5 consistently overestimated threshold, although responses were repeatable.

jects by using linear ramps at 4.15 µm/sec. The mean appearance thresholds of the first 2, 4, 6, 8, and 12 stimuli were compared. Four or more stimuli provided similar thresholds (figure 6).

Comparison of VDT of index finger in healthy subjects by using 3 algorithms of testing. The VDT of the index finger of 20 control subjects was tested on separate days with forced-choice, linear ramp (4.15 µm/sec), and Békésy (0.5, 1, and 2 JND/sec) algorithms. The results from the linear ramp and Békésy algorithms were compared with the results of the forced-choice algorithm for accuracy, repeatability, and speed. The linear ramp at 4.15 µm/sec markedly and significantly overestimated threshold but repeatability appeared good (figure 7). Békésy testing with exponentially increasing amplitudes of 0.5 and 1 JND/sec underestimated threshold 3 of 4 times, with a significantly smaller mean threshold for both rates in the 2nd trial (figure 7). Békésy testing at 2 JND/sec overestimated threshold significantly in both the 1st and 2nd trials.

Repeatability is an important criterion by which to assess the usefulness of a test such as VDT. Figure 7 shows in box and whisker figures the variability (either as displacement or as JND) for different algorithms of testing. Results of all algorithms of testing were as or more repeatable than those of forced-choice testing. To illustrate repeatability for an algorithm showing favorable characteristics, inspect the box and whisker figure for algorithm 3 (Békésy with a rate of 1 JND/sec). Some subjects had identical thresholds, 50% had thresholds within 0.6 JND of each other, 75% had thresholds within 1.1 JND, and all had thresholds within 2.1 JND. If one appreciates that 1 JND reflects the just noticeable difference that can be perceived, or 1 level of testing in the forced-choice algorithm, it appears that repeatability is good.

On average (SD), the time taken to estimate threshold using the forced-choice algorithm was 9.1 minutes (4.4). Times for estimating threshold using the Békésy algorithm at 0.5 JND/sec were 1.3 minutes (0.4); at 1.0 JND/sec were 1.0 minutes (0.2); and at 2 JND/sec were 0.9 minutes (0.1)—all significantly ($p < 0.001$) smaller in forced-choice testing. The average (SD) to estimate threshold using linear ramps at 4.15 µm/sec was 0.8

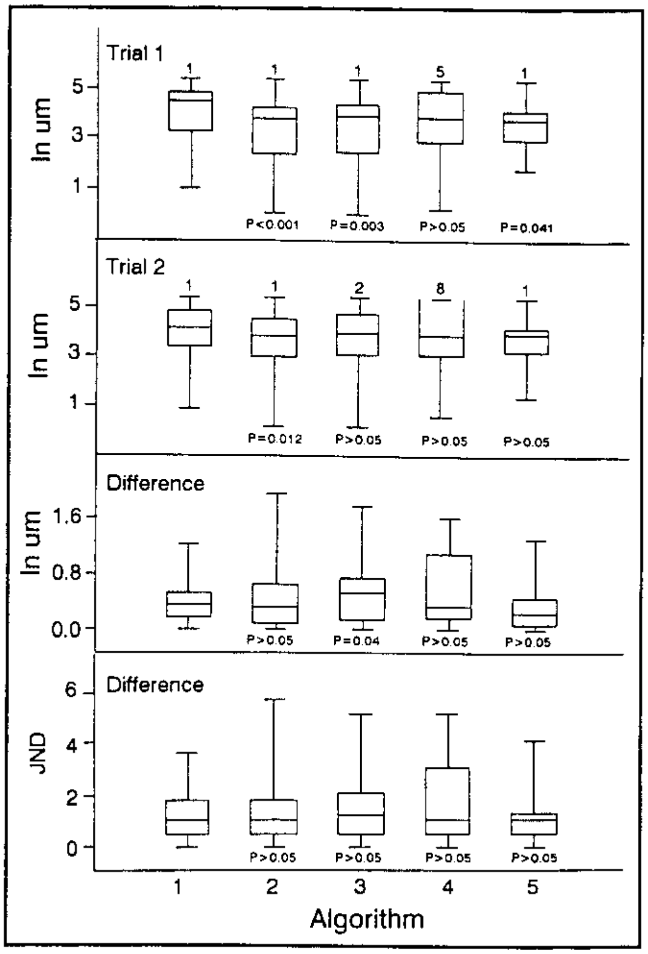

Figure 8. The distribution of vibratory detection thresholds (VDTs) of the great toe in 20 patients with mild neuropathy, and the differences in these thresholds when VDT was estimated on 2 occasions. The algorithm of testing is the same as shown for figure 7. The number above the box and whisker figures reflects the number of patients who were insensitive. Compared with forced-choice (1), Békésy testing with null stimuli testing at 0.5 JND/sec (2) and at 1 JND/sec (3) performed well by the criteria of accuracy and repeatability. Békésy testing with null stimuli at 2 JND/sec (4) frequently overestimated threshold. Linear ramps (4.15 μm/sec) with null stimuli performed well in this group of patients, but have been shown to overestimate threshold in sensitive fingers (see figure 7).

minutes (0.1) ($p = 0.003$).

Comparison of VDT of the great toe in patients with mild neuropathy with 3 algorithms of testing. The VDT from Békésy and linear ramp testing (4.15 μm/sec) were generally lower (sometimes significantly) than from forced-choice testing (figure 8). Whereas only 1 patient was insensitive using forced-choice testing, 5 and 8 were insensitive when Békésy testing (2 JND/sec) was used on the 1st and 2nd occasions, respectively. Linear ramp testing at 4.15 μm/sec provided accurate results in contrast to what had been found in healthy subjects. The speed was less than with forced-choice testing. Repeatability was, on average, not different among algorithms.

On average (SD), time needed to estimate threshold using forced choice was 9.2 minutes (2 to 3 minutes)—not significantly ($p > 0.05$) different than the time needed to estimate threshold of the finger in healthy subjects. Times needed to estimate threshold using the Békésy algorithm using 0.5 JND/sec was 3.9 minutes (1.5), 1.0 JND/sec was 2.7 minutes (1.0), and 2.3 minutes (0.7)—all significantly less ($p < 0.001$) than for forced-choice testing. The average time needed for linear ramp testing at 4.15 μm/sec was 2.9 minutes (1.2)—significantly ($p < 0.001$) less than for forced-choice testing.

By the criteria of accuracy, repeatability, and speed, the Békésy algorithms with null stimuli at 0.5 and 1 JND/sec provided an accurate and fast threshold.

Discussion. There is already considerable information on the physiologic characteristics of receptors and neural systems underlying vibratory sensation.[10-12] The vibratory detection threshold has been quantitated in health and neurologic disease.[1,12-17]

Engineering advances, particularly the availability of powerful and inexpensive microprocessors, reliable thermoelectric units of different sizes and power, and electrical motors with displacement proportional to current have made it possible to design sophisticated systems to assess VDT, touch-pressure thresholds, WDT, and CDT. These systems can provide stimuli with appropriate and defined waveforms of known amplitude that can deliver stimuli of precise waveform and over a broad range of amplitudes. To take advantage of this degree of sophistication and not to introduce extraneous stimuli, the transducer should not be hand-held but machine-held at a constant load and should not be moved from the surface of the skin between stimuli.

To exploit the special advantages of the system approach, the steps in testing and finding threshold must be optimal and programmed, and subject conditions (wakefulness, cooperation, and lack of distraction) must also be optimal. Improper algorithms of testing might themselves lead to faulty results.

Insufficient attention has been directed to the influence of the specific algorithm of testing on response characteristics. Assuming that the test environment and the subject and patient conditions are optimal, we still know too little about the effect on threshold of the characteristics of the waveform, rate, and kind of increase in amplitude of stimulus, number of trials used, use or not of null stimuli, use or not of alerting cues for test events, continuous versus step testing, and threshold criteria (appearance threshold, mean of appearance and disappearance thresholds, and forced-choice threshold). In a recent study,[9] we reasoned that, ideally, it would be desirable to test various approaches in a series of normal subjects and patients with a broad range of sensory impairment. However, the magnitude of the problem rendered such a patient-based evaluation problematic. We therefore used extensive computer-based simulation to evaluate the rules of testing to find threshold in various conditions when the true threshold was known.[9]

In the present study, we assessed VDT by using a new vibratory transducer that reliably provides sinusoidal oscillation at 125 Hz over a wide range of amplitudes. The overall objective was to identify algorithms of testing that would allow accurate, repeatable, and fast measurement of VDT, which then could be used in a new computer-assisted sensory examination system (CASE IV).

The Békésy algorithm (at 0.5 or 1 JND/sec) provided thresholds that were as accurate and repeatable as those from forced-choice testing, and faster to obtain. The rate of increase of stimulus amplitude affects threshold markedly both in linear ramp and Békésy testing. Fast linear ramps overestimate threshold, especially at sensitive sites such as the finger. The reason for this overestimation may be explained by failure to "freeze" the stimulus amplitude to the magnitude at which it was first felt because reaction time was too slow considering the rapid rate of stimulus amplitude increase.

The cueing lights used to indicate "get ready" or "test in progress" were not an important variable in threshold estimation. The observer apparently provided sufficient instruction and surveillance so that the additional light cues were unnecessary.

The number of trials needed to get stable threshold estimates by using linear ramps was low—4 trials appeared to be sufficient.

We did not perform tests comparing linear ramps or Békésy algorithms with, as compared to without, the use of null stimuli. We did observe, however, that for both healthy subjects and neuropathic patients, use of null stimuli provided a mechanism so that the time of the next stimulus could not be anticipated. Use of null stimulus was also a mechanism to instruct the patient to make the distinction between externally and internally derived stimuli.

Our results suggest that the Békésy algorithm, using stimuli that increase exponentially, is clearly preferable to the use of linear ramps for 3 reasons: (1) stimulus magnitude increases with time based on just noticeable difference; (2) it is a quick method of testing both sensitive and insensitive parts or persons; and (3) thresholds obtained with it are accurate when compared with those obtained using forced-choice testing.

Might use of linear ramps and mean values of appearance and disappearance thresholds[18] also provide a good algorithm for use in automated systems? Our studies suggest that satisfactory linear ramp rates cannot be chosen because they are either too slow for insensitive parts or too fast for sensitive parts to be optimal for automated systems.

Should the Békésy algorithm at 0.5 or 1 JND/sec replace forced-choice testing for use in automated systems? This study suggests that it might. There are situations, however, when the forced-choice approach is preferable. When the patient cannot depress the response key and must verbally report the response to an observer or is too thoughtful about responses (too slow), the forced-choice algorithm is better. A further reason for using the forced-choice approach is that the patient might have positive symptoms (eg, paresthesia) that are hard to discriminate from vibratory stimuli. Also, when threshold approaches the upper range of magnitudes tested, Békésy testing will result in a threshold not being ascertained whereas with forced-choice testing it may be ascertained. Finally, forced-choice testing should be done when the patient aborts the test serially—eg, 2 times—because he or she signals sensitivity during a null stimulus.

We therefore suggest that Békésy testing—eg, at 1 JND/sec—or preferably forced-choice testing be used for testing patients for clinical purposes, for epidemiologic studies, and for controlled clinical trials. It will be necessary to develop reference values for test, site, specific stimulus conditions (eg, 0.5 or 1 JND/sec), age, sex, and other variables for each of the algorithms of testing to be used to determine whether a result in a patient being tested is normal or abnormal.

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