EVALUATION OF SENSIBILITY AND RE-EDUCATION OF SENSATION IN THE HAND

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Accurate indications, advere reactions, and dosage schedules for drugs are provided in this book, but it is possible that they may change. The reader is urged to review the package information data of the manufacturers of the medications mentioned.

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PREFACE 4^{TH} PRINTING

EVALUATION OF SENSIBILITY AND RE-EDUCATION OF SENSATION

When I wrote *Evaluation of Sensibility and Re-Education of Sensation* in 1980, I had finished my Plastic Surgery residency at Johns Hopkins Hospital and Hand Surgery fellowship with Dr Raymond T. Curtis in Baltimore. I was beginning my private practice and writing my first book. It was an amazingly exciting academic time. It is now 35 years later, and time to look back at the impact of my first book and decide if it is time for a new printing of this material.

I remember that in preparing the first edition of this book, I would walk and think up subtitles for the chapters. I would go to the Hopkins Library, find each original reference, and actually read it. The drafts of each chapter were hand written and then typed. The finished draft was taken to Williams & Wilkins, the publishing company, with me praying they would accept to print and publish it. Today, writing is composed upon the computer, saved to the hard drive, reformatted by a graphic designer, and published on line. A huge transformation of the publication process. Today, I have published five different books, each with various iterations and subsequent printings. I have published more than 450 scientific papers in peer-reviewed journals. I have published more than 100 book chapters in other doctors' books. Most of this material is available online, especially at Dellon.com.

THE MATERIAL PUBISHED IN THIS, MY FIRST BOOK REMAINS RELEVANT, AND YET UNAVAILABLE TO MOST READERS INTERESTED IN THE SUBJECT OF SENSIBILITY EVALUATION, THE HISTORY OF NEUROSENSORY TESTING, AND SENSORY REHABILITAITON.

It is time for my early research and that of the researchers before me to be made available on the internet. The first edition has been "remastered" as they say in the music industry. Simply put, the book, which was never placed into digital media, has been retyped and reformatted, but otherwise unchanged from the original. Only this Preface has been added. Towards that point, great thanks go to Elaine Lanmon (justsk8@gmail.com), the graphic designer, Scott Eagle (scott@highlevelstudios.com), my webmaster for Dellon.com, and Lightning Source (http://www.lightningsource.com), the online publisher. Finally, to Luiann Olivia Greer, my wife, and partner since 1997, I give profound thanks and gratitude for providing the peaceful and creative environment in which I have been able to research, write, and educate.

The contents of the book can be downloaded in its entirety and obtained as a bound version from Amazon.com, or each of the three different parts of the book can downloaded separately, for free at Dellon.com.

From the perspective of 35 years, hindsight reveals that the first section of Evaluation of Sensibility and Re-Education of Sensation, Back to Basics, has material still not available in any collection anywhere else. For this section alone, historically, this book needed to be reprinted, so that young investigators today can read and see the experience of the early workers in the field of neurosensory anatomy and morphology. The second section, Evaluation of Sensibility, introduced the concept that examination of the hand must be done with instruments and techniques that are based upon neurophysiology, standardized, and using normative data. This section introduced my Moving Two-Point Discrimination Test, which has become adopted world-wide as a measure of large fiber regeneration related to touch perception and innervation density. The pattern of sensory recovery described in this section, which I described while still a Johns Hopkins medical school student, has been confirmed and the concepts applied to neurosensory testing in the feet and the face. New equipment, such as the Pressure-Specified Sensory Device (PSSD) has been developed by myself based upon the principles in this chapter, and this device is now an accepted standard in evaluation of sensibility. The third section, Re-Education of Sensation, proved to be the starting point for a widespread international movement of techniques I developed, again while a medical student, and now used routinely for rehabilitation of the hand, and the foot, after nerve injury and repair.

I remain immensely proud of my first book and am delighted to be able to present its content afresh on the world wide web.

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2015

FOREWORD

RAYMOND M. CURTIS, M.D.

This book more than fulfills its author's purpose by providing a bridge that connects the Hand Surgeon to Neuroscientist, each of these to the Hand Therapist, and all to the patient with an injured peripheral nerve. The book is scholarly and authoritative, yet written in a way that easily translates the complex material. The content is comprehensive, and arranged to be of maximal educational benefit. Each statement is referenced, and the reference appears both at the end of the chapter and at the end of the book in a separate bibliography, which will ease future recall.

To place this book in historical perspective we must realize that since Sterling Bunnell's classic monograph in 1944, the vast majority of subsequent texts have dealt with either specific surgical techniques or anatomic studies related to the hand. The trend is toward published symposia or multi-authored texts. Even the emphasis on rehabilitation has excluded the sensory aspects. Thus, Lee Del-Ion's contribution is unique, and we are indeed indebted to him for this tremendous undertaking. His broad background in basic science and research, his search of the past for clues to the future, his more than a decade of meticulous evaluation of patients with impaired peripheral sensibility have culminated in this single-authored book. The book is reminiscent of Bunnell, not only in specific areas, for example, use of comparative anatomy to discuss the evolution of the sensory end organ as Bunnell did for the upper limb, but also in original contributions. Dr. Dellon demonstrated in primates the fate of sensory corpuscles after denervation and following nerve repair. Dr. Dellon is responsible for urging that our evaluation techniques for sensibility have a neurophysiologic basis. He demonstrated the pattern of sensory recovery following nerve repair, initiated the use of vibratory stimuli administered by tuning forks for peripheral nerve problems, added the terms "moving-touch" and "constant touch" to our vocabulary, and conceived the moving two-point discrimination test. Equally important he developed and refined sensory rehabilitation to be consistent with this evaluation scheme, incorporating specific sensory exercises at the appropriate time in the recovery process. These exercises emphasize finger movement and object recognition. This Sensory Re-education has produced unparalleled results.

Outstanding is the model of the sensory endings in the fingertip, which is found in Chapter 2. The Section on Evaluation of Sensibility critically reviews the relevance of every previously described clinical test. The separate existence of a vibratory sense is disproved. Finally, the author's own evaluation scheme is described in detail for each potential clinical setting. The Section on Reeducation of Sensation begins with the most comprehensive review of end-results of nerve repairs, in which essentially every published report is collated and reduced to a common reporting format. The historical and technical aspects of

Sensory Re-education will be welcomed by a world in which this concept increasingly is being accepted, and already producing improved results.

The volume clearly has been a labor of love of many years for Lee. He has recognized that knowledge develops from the thousands who precede, and to these he shows his gratitude. We are under a heavy debt to him. His volume takes its place as one of the outstanding contributions to medicine and biology.

Baltimore 1980

FOREWORD

ERIK MOBERG

Once the world knew only two centers of culture, one in Europe and the other in China. Only distorted rumors connected the two, arriving over endless camel trails. Neither center influenced the other. In order for Marco Polo to see in person these two different worlds and initiate communication, he needed a young unbiased brain together with an ability for fearless traveling.

In important parts of basic neuroscience and clinical nerve work the situation has been similar. On the one hand, neurophysiology is developing a micro-"electrology" capable of tracing even single nerve impulses. In animal experiments computerized studies are revealing much of great interest. On the other hand, the clinical observations of modern hand surgery have added a wealth of new knowledge concerning hand function, impossible to obtain in the animal laboratory. Patients provide the examples to distinguish the different qualities of sensory function and between afferents to the conscious and unconscious level. This is the basis for all rehabilitation. Yet between these two fields the contacts are almost missing. There is even a barrier in their terminology.

The young author of this book is the first one to connect these two antipodes, each so important to the other. Dr. Dellon's enormous enterprise, to travel through and scrutinize modern physiology and other basic sciences and to summarize and combine these with modern hand surgery reminds one of the ancient explorer.

Sterling Bunnell in his "Surgery of the Hand.," in spite of the language barriers, reviewed almost all of the important literature. Similarly, as should be the rule in scientific work, Dr. Dellon has included important work from different times and languages. The references are not only mentioned, they are, when necessary, translated, read, and digested. (It is a pleasure to find even the rarely quoted but important work of Stopford from the l920's included.) And so the information in this book will no doubt remain for a long time the source by which less penetrating authors will escape.

Sensory Rehabilitation, which has been neglected for so long a time from our follow-up work, has now been elevated to an established position through the intense personal efforts of Dr. Dellon. A thorough description of the when and how is given as a necessary guide for this critically needed therapy.

And so this book is unique in the flood of hand surgery literature of today. No doubt it will give rise to conflicting opinions and controversy, which is the basis of all progress. After reviewing the established facts, the author guides the reader to many remaining unsolved questions. This book will find readers from many fields.

It has been a rare privilege to follow Dr. Dellon's work from his early beginning to this outstanding presentation.

Gotteborg 1980

PREFACE

The purpose of this book is to bridge the potential, if not actual, gap between those involved with the neurosciences and those involved with the care of the peripheral nerve. The bridge is a personal one; its construction begun 12 years ago, attempting to seek a firmer basis for understanding and, hopefully, correcting problems encountered in the operating room and the surgical follow-up clinics. It's a bridge whose final span will continually be under construction.

Research into the mechanisms of sensibility, the neural process which transduces external stimuli, has lagged enormously behind research into motor function. Yet, without sensation, the central, conscious perception or appreciation of those peripherally generated neural impulses, the hand is virtually immobile. Without sensation, visual control must be added to guide hand action. Since the mid-1960's, neurophysiologists and anatomists have brought microdissection, single-unit nerve recording, and electron microscopy to bear upon the sensory component of the mixed nerve. These insights have provided a more valid basis for understanding the sensory receptor population in the fingertip, for evaluating sensibility following nerve injury and repair, and for rehabilitating the hand.

However, as the basic scientist and the clinician evolve into ever more highly specialized areas, separation and loss of communication result in failure to utilize each other's vital contributions. It is, unfortunately, rare for either the clinician to read the basic science literature or the basic scientist to examine a patient. Surely fruitful areas for further exploration would arise from the latter, and answers to perplexing problems derive from the former.

It is hoped that the correlated view presented in this book will reach the medical student's lecture halls in microanatomy and classrooms in physical diagnosis. It is hoped that this bridge aids the peripheral nerve surgeons (be they hand, orthopedic, plastic, or neurosurgeons) in evaluating the hand with a nerve injury, in understanding the meaning of that evaluation, and in choosing and completing the indicated therapy, sensory re-education. It is hoped that neuroscientists reading this book will take pride in finding application of their "basic" contributions and be challenged to enter the clinical arena. Finally, it is hoped that this book provides more than a bridge, rather, a bond between the surgeon and the hand therapist, providing rational techniques to allow the patient to fulfill the maximum potential for sensory recovery in the shortest possible time.

The origin of our present misconceptions of sensory receptor morphology and physiology is explored in Chapter 1. These misconceptions are corrected in Chapter 2 with a contemporary model of the glabrous skin and in Chapter 3 with a distillation and interpretation of contemporary neurophysiology. The usually neglected sensory end organs are focused upon in Chapter 4, after denervation and in Chapter 5 after reinnervation. Evolution of my technique for evaluating sensibility comprises Chapters 6 through 9, which present a historical review of sensory testing, critically review alternative approaches to sensory testing, and culminate in Chapter 10, my personal approach to evaluating sensibility. Chapter 11 reviews the end result of nerve repair since 1940 and provides the data base for an historic control. The development, technique, and results of sensory re-education conclude the book in Chapter 12.

The text is designed for maximum educational benefit. Each Chapter has its own bibliography arranged numerically as the reference arises in the text. A combined bibliography, arranged alphabetically, precedes the index. The index is comprehensive, including both subjects and authors cited in the text. The referenced works have each been read, unless the reference is specifically attributed to another author's citation or quote. This required, in many cases, language translation. At the conclusion of most chapters is a section on clinical implications, transferring theory into practice. Where appropriate, new avenues for research are suggested. Where the work referred to is my own, the text is written in the first person. Some of this material, as noted in the bibliography, is "hot-off-the-press" and as such is not yet available in the published "scientific literature." In these instances, sufficient data has been included to justify the conclusions. Thus, this text represents a highly personal approach to its subject material. It is, however, an approach which I believe incorporates the basic science and clinical knowledge of today into a unified philosophy and application.

ACKNOWLEDGEMENTS

The single greatest factor permitting my dream of this book to become a reality has been the love and understanding of my boys, Evan and Glenn. The book represents an irreplaceable and precious commodity, time spent away from them. And certainly in the last 6 months of this book's preparation, even when I was with them, I was away. For their realization that the fulfillment of this dream was so important to me, and for their providing the peace of mind required for its fulfillment, I can only say, "Thank you" and "I love you."

The preparation of the book required assistance. I was truly fortunate to be able to work with two talented medical illustrators. Sue Seif did all the book's illustrations except Chapter 2. The illustrations for Chapter 2 are by Mark Lefkowitz and are an outgrowth of his thesis project. I had the privilege to be the scientific advisor to both Sue and Mark for their Master's Theses and have been delighted with the work they've produced for this text. I know their future illustrations will enhance the medical community beyond the foreseeable future.

The photographic contributions to this book are from three sources. Robert M. McCIung and Margo N. Smyrnioudis, from the Department of Audiovisual Services, the Union Memorial Hospital, did the studio staged photography for Chapters 6, 9, and 12. Raymond (Peter) E. Lund, RBP, FBPA, Director of Pathology Photography and Instructor in Pathology at the Johns Hopkins Hospital, and his staff, did the photomicroscopy for Chapters 5 and12, co-ordinated the special timing required to reproduce figures from journal texts which were kindly loaned from the Welch Library, and reproduced my patient slides into prints. Bryce Munger, M.D., Chairman of the Department of Anatomy of the Milton S. Hershey Medical Center, did the electron microscopy for the book, including the previously unpublished light micrographs of the Merkel cell-neurite complexes in Chapter 2. My deepest thanks to you all.

Special thanks to Walter Ehrlich, M.D., Associate Professor of Environmental Physiology in the Johns Hopkins School of Hygiene and Public Health. He combines both the literary skill of a linguist and the scholarly patience of a medical scientist. He was thus able to translate for us the works of Weber, von Frey, Valentin, and others. His is a unique contribution.

Finally, a thank you to Susan Vitale, Senior Editor, to George Stamathis, Production Coordinator, and to the production staff at Williams & Wilkins, my publisher. The completed book reflects their skill and experience, and I am deeply grateful for their efforts and professionalism.

CONTENTS

Section 2

Evaluation of Sensibility

Chapter 6

IT'S ACADEMIC BUT NOT FUNCTIONAL

INTRODUCTION

I believe hand surgeons have been handicapped at the start of their medical training. A person's perception of an event is conditioned by his prior training and experience. In medical school our approach to evaluating sensibility in the hand is derived from our lectures or teaching in neuroanatomy and physical diagnosis. As we grapple with this anew language" of neuroanatomy, we begin to be "indoctrinated." We are told that, "the posterior white columns, the fasciculus gracilis and cuneatus constitute the principal path for conduction of discriminative sensibility related to cortical function, conveying impulses from proprioceptors regarding position sense and movement, from tactile discriminators necessary for the proper discrimination of two points simultaneously applied and from rapidly successive stimuli produced by application of a tuning fork to bone ... (and from) appreciation of differences in weight and ability to identify objects placed in the hand by feeling them."[1] The anterior spinothalamic tract "transmits impulses of light touch ... the sensation evoked by stroking an area of skin devoid of hair with a feather or wisp of cotton. This sensation supplements deep touch (pressure) conveyed in the posterior white columns."[1] The lateral spinothalamic tract is "of tremendous clinical importance ... temperature and pain fibers are located in this tract."[1]

We learned our sensory examination in the "neurology" or "nervous system" segment of Physical Diagnosis,[2, 3] and it is designed to localize lesions in the central nervous system. Thus, touch is to be evaluated by "the touch of a finger … a wisp of cotton or a earners hair brush"[2] Position sense, temperature … pain (deep pressure is equated with pain) … two-point discrimination and stereognosis (a test of "cortical integration") are also suggested.[2] Currier[3] suggests "the sensory examination is difficult to perform well and interpret correctly. His exam includes "vibration ... with 128 cps tuning fork applied to a bony prominence . . . pain with a sharp pin ... temperature sensation with any warm or cool object ... deep pain ... by squeezing, light touch by a wisp of cotton., two-point tactile sensation ... and stereognosis tested in the hands." It is, therefore, perfectly understandable that 10 years later, when the young surgeon attempts to evaluate a hand with a nerve injury or after a nerve repair, his approach is one vaguely recalled from his "academic" days. It is further perfectly understandable that while such an approach may localize a lesion in the central nervous system, it may have little relevance to evaluating the recovery of useful sensation in the patient's hand (Fig. 6.1).

Figure 6.1 Academic versus functional. The neurologist's goal in evaluating sensibility is different from the hand surgeon's. Tests to evaluate spinal tracts and central nervous system pathways do not correlate with the ability of the hand to function.

"There is a real distinction between 'academic recovery' judged in terms of return of motor and sensory function and what may be termed 'functional recovery,' which is judged in terms of the patient's ability to return to complete social and economic independence."[4] This statement summarized the collective experience of the Nerve Injuries Committee of the British Medical Research Council after evaluation of their World War II studies. They chose the term "academic" to represent the classic or traditional neurologic approach to evaluating sensibility in the hand: pain was tested grossly with a pin or quantitatively with a spring-loaded, graded algesiometer; touch was tested grossly with a cotton wisp or quantitatively with calibrated, von Frey hairs. Tests for heat and cold "were not regularly employed since they did not provide any additional information of clinical significance."[5] Academic recovery was graded according to the outline originally proposed by W. B. Highet, and recorded by Zachary[6*]:

Stage 0: absence of sensibility in the autonomous zone of the nerve.

Stage 1. recovery of deep cutaneous pain sensibility within the autonomous zone.

Stage 2: return of some degree of superficial pain and tactile sensibility within the autonomous zone.

Stage 3 return of superficial pain and tactile sensibility throughout the autonomous zone with the disappearance of over-response.

Stage 4: return of sensibility as in Stage 3 with the addition that there is recovery of two-point discrimination within the autonomous zone.

"Functional recovery was judged by the use made of the injured limb by the patient."[4]

Although this approach indicates a recognition of the fact that the results of the classic physical diagnostic techniques were not predicative of a patient's ability to utilize his hand, the credit for bringing this to worldwide attention belongs to Eric Moberg. Although Moberg has said: "The distinction between academic and functional recovery is one of the important contributions to nerve surgery made by Seddon and his associates in Great Britain,[8] Moberg, himself, has spent at least two decades(7-14) further emphasizing, refining, and demonstrating the importance of functional sensory testing.

MOBERG

Erik Moberg is one of the giants of Hand Surgery. His influence is felt in many spheres, and he continues, in "retirement," to be innovative and persuasive, for example, in the rehabilitation of the tetraplegic.[15†] His unceasing emphasis on the evaluation of functional sensibility for more than 2 decades deserves all our thanks. In 1958, the *Journal of Bone and Joint Surgery* gave 22 pages of text for Moberg's then iconoclastic and now classic paper on "Objective Methods for Determining the Functional Value of Sensibility in the Hand.[9] Written from the Hand Service, Sahlgren Hospital, Gothenberg,

[*] This classification is often referred to as "Highet's Classification," yet we find it in Zachary' chapter and little else ever mentioned of Highet. Recently, I found the answer to this: Seddon[7] writes "W Bremner Highet joined us at the outbreak of the Second World War. This talented young New Zealander was awarded the Jacksonian Prize by the Royal College of Surgeon of England for an essay on nerve injuries. The closure of the Mediterranean Sea left only the Cape route for the evacuation of men injured in the fighting in the Desert War. As a result of the shortage of transport shipping many of them piled up in South Africa. Highet was chosen to look after those who had suffered nerve injury. He was sent by sea; the ship was torpedoed and there were no survivors."

[†] He prefers tetraplegic to quadraplegic (a mixture of Latin and Greek).

Sweden, this paper clearly stated the problem, "it has been borne home to me with the passage of years how little the results of the customary tests of sensibility in an injured hand correspond with the actual ability of the patient to use his hand." In this paper, Moberg described two new objective tests; the "picking-up test" and the ninhydrin test, now universally known. He further coined the terms "precision sensory and gross sensory grip." He resurrected the term "tactile gnosis" to replace "stereognosis." He also correlated results from using all the then known academic and functional tests on a series of patients. Moberg elaborated upon his work in the journal NeuroJogy,[10] commenting in a footnote "when the investigation was completed in the main four years ago, it was realized that its results must entail a complete change in the attitude to the current methods of examination. For this reason, it was decided to delay publication of the results until after they could be checked still further. This was done on an extensive series in regard to diagnosis, therapeutic measures and judgment of disability, and the results were corroborated in full."

On May 14, 1962, Erik Moberg gave the first Annual Sterling Bunnell Lecture to the American Society for Surgery of the Hand on "Aspects of Sensation in Reconstructive Surgery of the Upper Extremity."[8] Although l had associated the phrase "without sensation, the hand is blind," to Moberg, primarily from the emphasis in his writings, and his picture of a fingertip with an eye in its pulp (Fig. 6.2), Moberg credits Bunnell with writing that when sensory function is lost, "the so-called eyes of the fingers are blind." (In reading Bunnell's nerve repair paper for Chapter 11, I recently found this statement.[9])

That Moberg possessed that wonderful (and rare) character trait of critical review of one's own work is evident in the published Bunnell Iecture.[8] Moberg described "limitations" then on the usefulness of his ninhydrin test. While restating that it is the only objective test of recovery, of nerve fibers, therefore, making it valuable in "children and malingerers," it is not useful in injuries to the brachial plexus or for skin grafts or flaps, it is useful after nerve suture only when prints are absent, and technical accuracy is necessary." The ninhydrin test essentially documented return of function to sweat glands, not a sensory function. Since sweat glands are innervated by very thin sympathetic fibers, the recovery of sweating should parallel recovery of pain and temperature (see Chapter 7). This observation, that recovery of sweating parallels recovery of protective sensation, has been confirmed again recently.[17] As Moberg, himself, demonstrated, perception of pain and temperature do not correlate with functional recovery.

Moberg was the first person, of whom I am aware, who attempted to correlate clinical sensory tests with hand function, and who recognized that certain clinical tests quantified the simple *"yes"* or "no" responses of other tests (see Table 6.1). Of interest is Moberg's comment that "I have not been able to find any report on a method of grading the function of the hand that could be used for the comparison."[10] Moberg began by defining hand function in terms of "what the hand can do," i.e., grips

(Fig. 6.3). The precision sensory grips included those necessary to screw on a bolt, wind a wristwatch, sew with a needle, knot a string, and button or unbutton. The gross-sensory grips included the ability to work with a heavy handle, like a wheelbarrow, use a spade, manipulate a doorknob, hold a bottle, or carry a basket. Utilizing the tests in Table 6.1, he studied 10 patients with previous median nerve injury who had recovered good motor function and were free of paresthesia. He studied the correlation between both the classic academic and his functional sensory tests with the patient's hand function as judged by sensory grips, the picking-up test, the patient's own opinion of his hand function, and the appearance of the hand (wear marks).[9, 10] Early in his study, Moberg chose to eliminate temperature testing because it "gives no more information than other methods," and vibration because "most joints of the hand are innervated from two sources."[10]

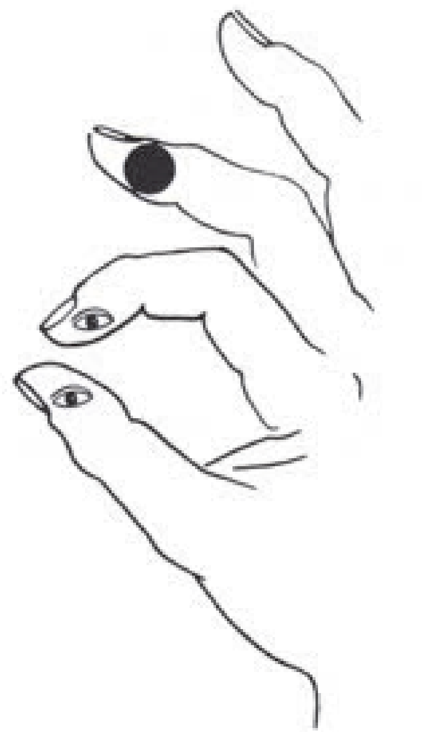


Figure 6.2 The eyes of the fingers. (reproduced with permission from E. Moberg: *Hand Surgery,* ed 1, Flynn JE (ed.). Baltimore: Williams & Wilkins, 1966[11])

Moberg's Conclusion

"It turned out that none of the known methods for examining the modality of touch or pain (or temperature or vibration) gave results which corresponded with the functional ability of the hand. Most of these tests were ... misleading. They are not good for grading disability and planning reconstructive surgery in the hand. The Weber twopoint discrimination test proved to give accurate information on the functional value of the sensibility in the hand."[10]

Table 6.1
Clinical Sensory Tests of Hand Function[a]

Quality	Testing Method	Quantitative Measurement
Touch	Cotton wool, strips of paper	von Frey hairs
Pain	Pin stick	Algesiometer
Localization	Localization of simple touch	Measurement of error
Temperature	Warm and cold objects	Degrees of temperature
Tactile gnosis	Writing digits on pulp, tactual recognition of objects, Seddon coin test, picking-up test	Weber two-point discrimination
Vibration	Tuning fork (128 cps)	

[a] Adapted from E. Moberg.[10]

Figure 6.3 Functional sensation must be related to "what can the hand do?" (Reproduced with permission from E. Moberg: : *Hand Surgery,* ed 1, Flynn JE (ed.). Baltimore: Williams & Wilkins, 1966[11])

Moberg's Specific Results

When two-point discrimination was 30 to 40 mm, there was "a certain capacity" for gross grip and a protective sensibility. Digit writing was found to give results that correlated with Seddon's coin test and two-point discrimination, but had practical shortcomings (clinically difficult to do and standardize). Seddon's coin test (an ability to distinguish whether a coin had a rough or smooth edge) correlated with two-point discrimination when two-point discrimination was "below 12 to 8 mm." But the coin test results "cannot be given in figures" and therefore it "cannot be used to distinguish between degrees of tactile gnosis lower than ... these figures."[10] Gross sensory grip was absent if two-point discrimination was greater than 40 mm. The picking-up test was possible if two point discrimination was less than or equal to 12 mm. Von Frey's hair results only roughly correlated with two-point discrimination testing, e.g. all patients with two-point discrimination less than 15 mm had a touch threshold less than or equal to 1.0 gm (however, some fingertips with two-point discrimination greater than 40 mm also had touch thresholds of 1.0 gm). Moberg was later to write that "some tactile gnosis" equaled a two-point discrimination of 6 to 15 mm, whereas normal equaled a two-point discrimination of 3.5 mm."[8] Moberg was still later to write that gross grip required two-point discrimination worse than 12 to 15 mm, but better than 30 to 40 mm, good tactile gnosis is hardly present if values are higher than 8mm."

NEUROPHYSIOLOGIC BASIS FOR MOBERG'S OBSERVATIONS

A firm basis for understanding clinical observations on sensibility in the hand has been provided by Mountcastle and his colleagues in neurophysiology (see Chapter 3). Unfortunately, this basic scientific foundation has failed to reach most practicing surgeons and is only now beginning to be emphasized by those few who have realized what a powerful tool it is in interpreting clinical problems. (lndeed, this is one of the reasons for writing this book!)

Table 6.2
Sensory Tests Used to Evaluate the Various Nerve Fiber Populations[a]

Clinical Test	Sensation	Fiber/Receptor Population
Pin	Pain	Free nerve endings
Heat	Temperature	Free nerve endings
Cold	Temperature	Free nerve endings
Cotton wool	Moving-touch	Quickly-adapting
Finger stroking	Moving-touch	Quickly-adapting
von Frey hair	Constant-touch	Slowly-adapting
Weber test	Constant-touch	Slowly-adapting
Picking-up test	Constant-touch	Slowly-adapting
Precision sensory grip	Constant-touch	Slowly-adapting
Gross grip	Constant-touch	Slowly-adapting

[a] Reproduced with permission from A. L. Dellon: *Contemp Orthrop* 1:39–42, 1979.[19]

Table 6.2 Sensory Tests Used to Evaluate the Various Nerve Fiber Populations(a)[(a) Reproduced with permission from A.L. Dellon:*Contemp Orthrop* 1:39-42, 1979(19)]

In 1969, I made two simple lists: one was of extant clinical tests of sensibility and the other was of presumed neurophysiologic group of sensory fibers being tested (see Table 6.2). This list was "cut" from my earliest paper[18] by the reviewing editors, and did not appear until recently.[19] When I considered Moberg's "grips" as requiring primarily the ability to perceive an object that was in constant contact with the fingertip, such as *holding* the sewing needle or *holding* the milk bottle while pouring, it became clear that these static grips required an intact slowly-adapting fiber/receptor system. Finger stroking and cotton wool wisps required perception of movement and, therefore, tested the quickly-adapting fiber/receptor system. Clearly then, the results of finger stroking or moving a cotton wisp across the surface of the finger would not correlate with hand function as defined in terms of these grips. However, von Frey's hairs and the Weber test both required perception of an object in constant-touch with the fingertip, and therefore, did test the slowly-adapting fiber/ receptor system. It would appear, at first, that but 1 of these test results should correlate with hand function, whereas Moberg found that only those of the Weber test did. My explanation for this is that the von Frey hair measures the threshold: a single nerve fiber may successfully regenerate, re-innervate a group of Merkel cell-neurite complexes, mature and, if that peripheral sensory field is tested, give a low or normal threshold for pressure. But, tactile gnosis, as defined by Moberg, required the ability to discriminate, and this requires, in Mountcastle's terms, (multiple) overlapping peripheral receptive fields, or a high innervation density. The Weber test measures the peripheral innervation density of the slowly-adapting fiber/receptor system. Therefore, Moberg's finding that only the results of the Weber two-point discrimination test correlated with hand function can be given a neurophysiologic rational *if* hand function is defined in terms of Moberg's static grips. The picking-up test (discussed in detail below) as practiced by Moberg, primarily required the performance of a static grip (Fig. 6.4), not object recognition.

In the remainder of the Chapter, I will review in detail the Weber test and other sensory tests, since, as Moberg[8] said, the tools are still crude and must be improved." In Chapters 8 and 9, I will present two "improved tools."

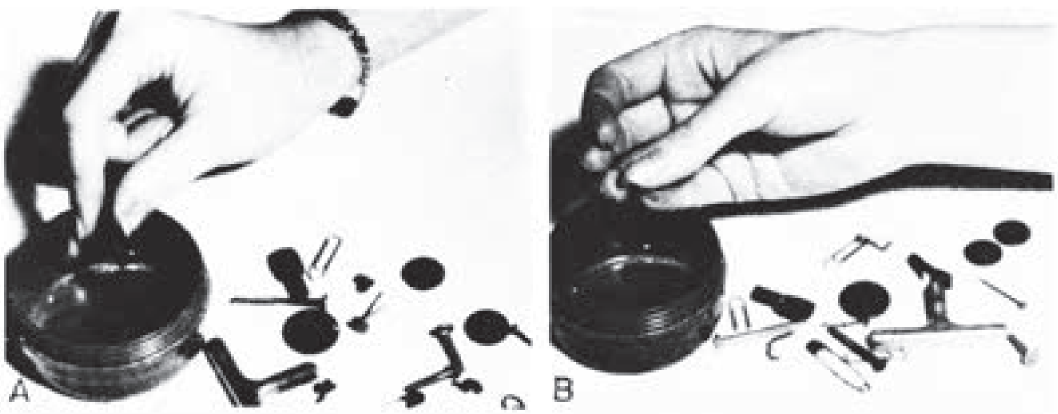


Figure 6.4 Moberg's picking-up test is primarily a static test, in which an object is picked up and then placed into a container. The patient is not asked to identify the object.

WEBER TEST

In 1853, Ernst Heinrich Weber, Professor of Anatomy at Leipzig, described a test of sensation distinguished by its ability to give a quantifiable test result. He described the use of calipers, whose points were held against the skin, at different distances apart, until a distance was found at which the subject could no longer distinguish one from two points in contact with the skin.[20] Weber emphasized that the compass ends should not be sharp, but rather be rounded (abgerundeten Spitzen). Weber also recognized that he was measuring what we call "innervation density." He wrote, "The more richly innervated and therefore, more sharply sensitive a piece of skin is, the more clear and correct one can sense the difference between two touched spaces." Weber found the most sensitive part of the body for discrimination was the tip of the tongue, then the fingertip.

The ability to record a number after a test had scientific appeal, and we find many of the earlier careful and critical investigators using this test. For example, Silas Weir Mitchelt[21] in discussing his sensory testing techniques during the American Civil War, emphasized not only that the compass must have rounded tips, but also that the test could not be done in the presence of hyperesthesia or paresthesia. In Boeke's laboratory in the 1920's, Doctor Stenver, one of Boeke's coworkers, accidentally cut the dorsal sensory branch of his right ulnar nerve. This was "repaired" and the recovery of sensation followed: two-point discrimination1 initially 50 mm decreased to 13 mm 12 months later.[22] In the late 1930's, McCarron[23] studied sensory recovery in skin grafts: "Completeness of the return was also checked by a comparison of the two-point discrimination of the graft with normal skin." In the early 1960's, detailed results of the Weber test were reported by Mannerfelt[24] in his study of sensory recovery in skin grafts and flaps (see Chapter 5), and by Onne[25] in his study of sensory recovery following nerve repair (see Chapter 12).

Moberg[9, 10] recognized several limitations of the Weber test, and further refined its use. The test requires patient co-operation and careful application. The environment must be quiet and the patient's fingertip or tested area carefully positioned and supported to prevent movement. Patient motivation is a factor, e.g., the compensation *caser* and thus the test is very subjective. If the numerical value for the two-point discrimination test is close to the width of the tested area, the test most likely is evaluating sensibility in the normal adjacent area. Thus, to say that the two-point discrimination of a 1-cm skin graft is 9 mm is to say that there is no two-point discrimination within the graft. Most importantly, the ends of the testing instrument must be blunted. A sharp compass end will elicit the perception of pain, not touch. Similarly, a blunt tip, pressed hard, will elicit pain, not touch. Accordingly, Moberg[11] has emphasized that two-point discrimination testing be done with the least possible pressure: "making the skin blanch where the points are applied should be avoided." Most recently, he has emphasized this by demonstrating that pressure at the end of the testing instrument depresses the skin causing adjacent skin to be stimulated, and, therefore, the examiner is actually testing a wider area than he believes he is testing.[14] (The "correct" pressure to apply is discussed further in Chapter 10.) Moberg requires seven out of 10 correct responses for a given distance to be accepted as the two-point limen.

Representative values for two-point discrimination in the normal hand are given in Tables 6.3, 6.4, and 6.5, adapted from the writings of the credited authors. Each of these studies was an actual evaluation of two-point discrimination in normal or control population Nevertheless, the accepted normal value for this classic two-point discrimination remains variously quoted. For example, Moberg[8] has written that a discrimination of 6 to 15 mm is required for usome tactile gnosis." Weiland et al.[29] have graded patients such that those with less than 10 mm had excellent function. Bell[30] has taken the 7 to 10-mm range as indicating "gross appreciation of two-point discrimination." Gel berman et al.[31] and Fess et al.[32] have listed the following classification, which is that accepted by the American Society for Surgery of the Hand: less than 6 mm is normal, 6 to 10 mm is fair, 11 to 15 mm is poor."[31] Millesi[28] has written that "although 80% of all persons (n = 80) had two-point discrimination value up to 3 mm, one cannot say that a value of 4 and more is out of the normal range. More than 6-mm two-point discrimination would tend to be beyond the normal range." The most recent comment on this is from Poppen et al.[33] Greater than 8 mm is "the level above which tactile gnosis is hardly present." It appears that the classic two-point discrimination test results leave considerable room for interpretation of normal functional limits.

Table 6.3
Normal Values for Two-Point Discrimination (mm)

	Volar Finger			
	Distal Phalanx	Cal-loused Pulp	Middle Phalanx	Proxi-mal Phalanx
Moberg[11]	2–4	4–6		4–6
Parry[26]	0.5–4		1–6	4–6
Gellis and Pool[27]	2–4			
Millesi and Rin-derer[28]	1.5–6			

Table 6.4
Normal Values: Two-point Discrimination (mm)

	Dorsal Finger		
	Distal Phalanx	Middle Phalanx	Proximal Phalanx
Parry[26]	1–6	1–8	1–12
Gellis and Pool[27]		2–7	

Table 6.5
Normal Values: Two Point Discrimination (mm)

	Hand				
	Dorsum		Palm		
	"Dor-sum"	Thumb Web	Thenar	Mid	Hy-poth-enar
Moberg[11]	8–11				
Parry[26]			4–11	4–15	5–9
Gellis and Pool[27]		5–15	4–8		4–8

Table 6.6
Average Time for Object Recognition in 40 Blindfolded Normal Subjects*

Object	Time (Sec)
Small coin	2
Large coin	3
Velvet	5
Plastic	4
Wool	5
Sandpaper	2
Rubber band	1
Screw	2
Safety pin	2
Key	2
Paper clip	2
Cork	2
Match stick	2

* Adapted from C. B. W. Parry.[26]

PICKING-UP TEST

In search of a test of hand function, Moberg[9] developed the picking-up test. The test was to answer the question, "What can the hand do?" He described the picking-up test in 1958:

> The subject is asked to pick up a number of small objects on a table and to put them quickly as he can into a small box, first with one hand and then with the other. After he has done this a few times, he is asked to do the same thing blindfolded. It is then studied how rapidly and efficiently he picks up the objects: comparison is made between his right and left hand, and likewise between his performance when he is blindfolded and when he is not. The test with blindfolding can be made harder by asking him to identify the objects as he picks them up. If his hand possesses normal sensibility, it can "see" even when the subject has his eyes closed. If sensibility in the median nerve region is impaired, the subject grasps the objects with his thumb and the ring and little finger instead of with the thumb and forefinger as he normally would.

The objects to be picked up in Moberg's test are several coins of different sizes, paper clips, safety pin, nails, screws, and two forms of wing nuts or bolts, which I cannot otherwise name from photographs of his kit (Fig. 6.4). Moberg records the results of this test in his charts or results tables simply with a plus or minus.

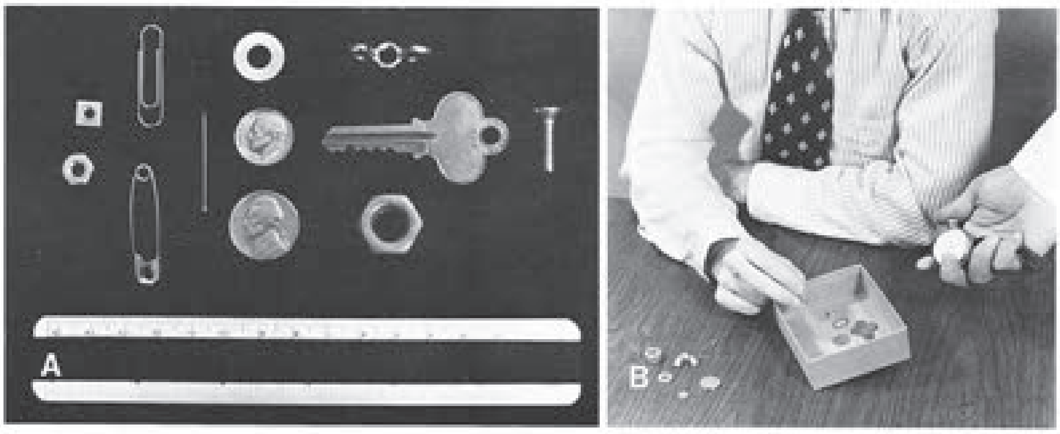
In 1966, Parry[26] published a set of times required for blindfolded, normal Englishmen (and women) to recognize common objects. Parry utilized a "recognition time" activity as a routine part of his sensory rehabilitation program. This program is discussed in detail in Chapter 12. An abbreviated table of his normal values is given in Table 6.6.

MODIFIED PICKING-UP TEST

The picking-up test as Moberg employs it, has at least two different functions, the results of which cannot be compared on different occasions. The Moberg test, as he, himself, states, requires motor function and therefore, if the tested function is the *success of placing the object into the cup,* motor function is clearly a dominant component. The grip required in that situation is one for pinching and holding an object within the fingers and requires perception of constant-touch and pressure (the slowly-adapting fiber/receptor system). It was this component that Moberg found to correlate well with the results of the Weber two-point discrimination test and this is what we could predict (as discussed above). However, if the subject is asked to *identify what he is picking up,* then we are testing another thing! The patient will be noted to attempt to twist and turn and move the object to accomplish this task. (The critical role of movement" is discussed in Chapter 8). Although this movement requires fine motor coordination, it also requires input from the quickly-adapting fiber/receptor system. The ability to identify objects is the essence of tactile gnosis. The time required for this recognition can be recorded for comparison at subsequent intervals to demonstrate progress or for comparison with normal.

I believe the goal of the picking-up test should be object identification, rather than object placement, and that the time required for recognition should be recorded with a stopwatch.[34]

The test can be made more meaningful by choosing objects of graded sizes, to present a series of graded difficulties. Furthermore, the objects are all metal to avoid object-temperature and texture as a distinguishing guide. In addition to size, each object has at least one other distinguishing feature. The objects I have chosen are illustrated in Figure 6.5 and listed in Table 6.7. The time required to identify each of these objects is listed for normal controls in Table 6.9. The patient is tested in two separate trials after first doing a timed, sighted, placement task to familiarize himself with the objects and their names (Fig. 6.5).



6.5 Modified picking-up test. *A*. Graded objects requiring increasing discrimination are used for object recognition. To familiarize patient with objects and allow patient and tester to agree on object names, a timed object placement test is run (*B*) prior to object recognition testing (see Tables 6.7 and 6.8). (Reproduced with permission from A. Lee Dellon and B. Munger, in press 1981.[34]

Table 6.7
Modified Picking-Up Test: Example[a]

Task	Trial (sec)	
	I	II
Not blindfolded:		
(Patient picks up objects from desk top and places them into a box)		
Blindfolded:		
(Examiner places object between thumb, index and middle fingers for identification)		
1. Wing nut		
2. Screw		
3. Key		
4. Nail		
5. Large nut		
6. Nickel		
7. Dime		
8. Washer		
9. Safety pin		
10. Paper clip		
11. Small nut (hex)		
12. Small nut (square)		

[a] Reproduced with permission from A. L. Dellon and B. Munger, in press 1981.[34]

We begin the test by placing the objects on a desk top, which offers some resistance against movement (as opposed to placing the objects on glass or plastic where they may easily slide as the patient attempts to pick them up). The patient's ring and little fingers are gently taped to the palm of the hand to prevent their inadvertent use (cheating!) (Fig. 6.6). First, a timed, sighted picking-up test is done with the objects to be placed in a container. This familiarizes the patient with the test objects and gives the examiner a chance to evaluate motor function. If motor function is insufficient, the test cannot be used further at that time. The test result is the total aggregate time for the picking-up test and depositing of all the objects. Next, the patient is "blindfolded" by having him look away. The examiner then chooses an object and places it within the patient's three-point chuck grip for the patient's object identification. The test is run through twice until all objects are identified, or until 30 seconds has been spent unsuccessfully attempting to identify an object. Time for each object is recorded separately. This is acceptable because we are attempting to evaluate sensibility, not motor function. There will exist a time during recovery when the patient will be able to identify the object by moving it across the surfaces of his fingertips, but won't be able to keep it between his fingertips easily because he cannot perceive how tightly he is holding it. The (quickly-adapting fiber/receptor systern is functioning at a more advanced level than the slowly-adapting fiber/receptor system (Fig. 6.7). Normal values (10, normal adults) for this modified picking-up and timed object recognition test are given in Tables 6.8 and 6.9. Correlation of tests of sensibility and hand function are discussed further in Chapter 10.

OTHER TESTS

"Seddon's" Coin Test

Although Seddon[35] is credited with developing this test, he states "Although I have used this test fairly regularly, I did not-as has been stated-invent it; I learned it from Riddoch in 1940 and he made no claim to be the originator." In the preface to his book, Seddon says he "learned from George Riddoch, neurologist." Seddon described the coin test and the "precursor of the picking up test."

The patient, whose eyes must be closed, is given a coin and asked to identify it. If he has a median nerve lesion ... he must not cheat by pushing the coin towards an area of normally sentient skin.

I believe this test is now of historic interest, except that coin identification is included in the object recognition test.

Porter's "Letter Test"

In 1966, Porter,[36] then an Orthopaedic Registrar at King Edward VII Hospital in Sheffield, England, described a "simple objective test for fingertip sensation which is believed to be a more accurate index of tactile sensation and is less time-consuming than the conventional tests." Porter uses metal type-setting letters, H, 0, U, V, Y of approximately 1.0 X 0.8 em in size with the letters standing out in relief. The patient "runs his fingertip over the surface as a blind person would read braille (Fig. 6.8)."

Five letters are examined unhurriedly in one hand, and the patient then applies the letters himself to the pulp under test. Incorrect identification or failure to identify the letter after 30 seconds is recorded as an error, and a score is obtained out of five.

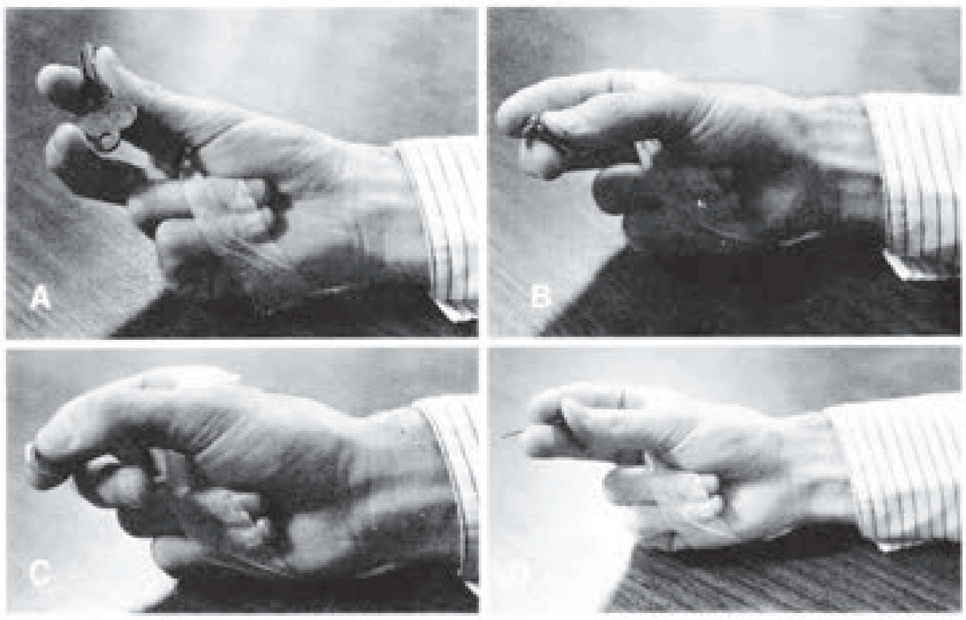


Figure 6.6 Modified picking-up test. To eliminate sensory input from ulnar innervation during timed object recognition, the ring and little finger are taped to the palm during the testing. Each object differs from another in the test series in a distinctive feature in addition to size (see Table 6.9). (Reproduced with permission from A. Lee Dellon and B. Munger, in press 1981.[34])

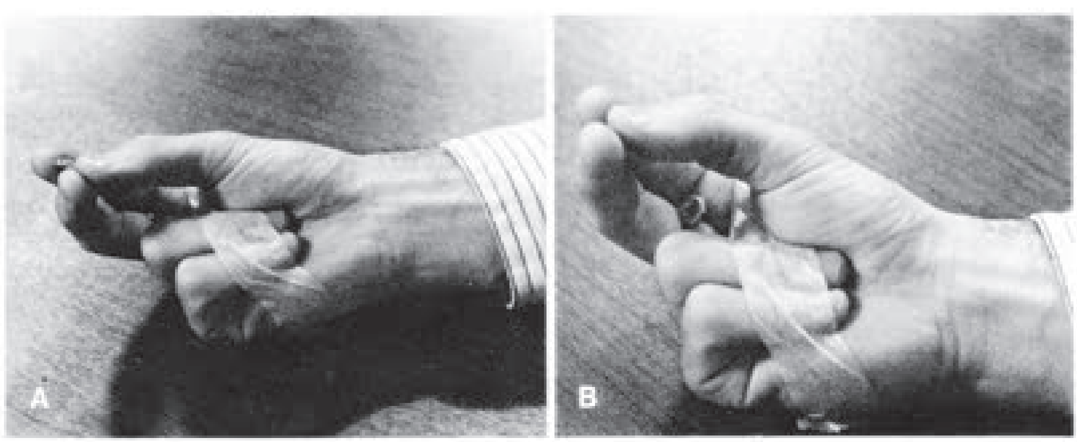


Figure 6.7 Modified picking-Up test. As sensory recovery progresses, there is a time when moving two-point discrimination has recovered and object can be correctly identified *(A),* but because the slowly-adapting fiber/receptor system is poorly recovered (there is no classic two-point discrimination) the patient is unsure how hard to pinch (how much pressure to exert) to maintain the object between the fingertips and the object falls *(B)*. (Reproduced with permission from A. Lee Dellon and B. Munger, in press 1981.[34])

Table 6.8
Modified Picking-Up Test[a]

Normal Values for Object Pick-Up[b]			
Trial I		Trial II	
Mean (sec)	Range (sec)	Mean (sec)	Range (sec)
13	10–19	11	9–16

[a] Reproduced with permission from A. L. Dellon and B. Munger, in press 1981.[34]
[b] n = 8.

Table 6.9
Modified Picking-Up Test[a]

Object	Normal Values for Object Recognition[b]			
	Trial I		Trial II	
	Mean (sec)	Range (sec)	Mean (sec)	Range (sec)
1. Wing nut	1.7	1–3	2.0	1–3
2. Screw	1.4	1–2	1.5	1–2
3. Key	1.5	1–3	1.6	1–2
4. Nail	1.7	1–4	1.5	1–2
5. Large nut	1.8	1–3	1.4	1–2
6. Nickel	1.8	1–3	2.0	2
7. Dime	1.7	1–5	1.3	1–2
8. Washer	1.8	1–3	1.7	1–3
9. Safety pin	1.6	1–2	1.6	1–2
10. Paper clip	2.3	1–5	2.1	1–3
11. Small nut (hex)	2.1	1–3	1.6	1–3
12. Small nut (square)	1.6	1–3	1.6	1–3

[a] Reproduced with permission from A. L. Dellon and B. Munger, in press, 1981.[34]
[b] n = 8.

Porter tested[47] normal patients for two point discrimination (mean of 0.33 em longitudinally and 0.31 em transversely over each fingertip, without any advantage radial versus ulnar), Moberg's picking-up test, and the letter test and compared them with 51 fingertip reconstructions (grafts and flaps). He found the results of the letter test "directly related to the two-point discrimination." Patients who could identify all five letters correctly had an average two-point discrimination of 4.5 mm, while those who could identify only one letter had an average of 7.5mm. Of eight patients who had a "positive" result in Moberg's picking-up test, the average two point discrimination was 7.3 mm and the average letter score was 2.3 compared to the 14 patients with "negative" results in the picking-up test whose averages, respectively, were 10 mm and .09 letters.

Although Porter's letter test offers another means of testing functional sensation, his results were not subjected to statistical tests of significance to demonstrate whether they offer an advantage in accuracy. To do the test requires the five letters. To compare any two authors' results would require the use of a similar set of metallic type. It would be interesting to know how Porter chose the five letters (out of 26 possible) and which one of the five was the most easily identified. His results do appear to confirm

Moberg's value of two-point discrimination less than 12 being required for finer tactile discrimination. However, it is probably not strictly correct (as described further in Chapter 8) to equate the results of these two tests, since in the Weber test the ends are held in constant touch with the fingertip, whereas in Porter's test, the letter is moved across the pulp, similar to digit writing. Thus, Porter's test is actually evaluating the quickly-adapting fiber/receptor system in addition to the slowly-adapting fiber/receptor system. I do not believe this test has practical clinical value.

Ninhydrin Test

This test was discussed earlier in this Chapter under "Moberg."

Plastic Ridge Device(33)

This device will be discussed in Chapter 8.

Wrinkle Test

It is common knowledge that our fingertips become wrinkled like prunes when we bathe. In 1973, O'Rain[37] observed that denervated skin lost this ability. An attempt to study this phenomenon in patients with nerve injury and nerve compression, comparing wrinkling with classic two-point discrimination and ninhydrin, has been reported (Fig. 6.9).[38] Patients with complete nerve injury had no wrinkling, no two-point discrimination, and no sweating. Patients with nerve compression had no correlation among these tests, that is, two-point discrimination was abnormal (greater than 15 mm), wrinkling was normal (in five of the eight patients), and ninhydrin staining was variable (normal in 3/8 and near normal in 5/8). I do not believe this test has clinical value.

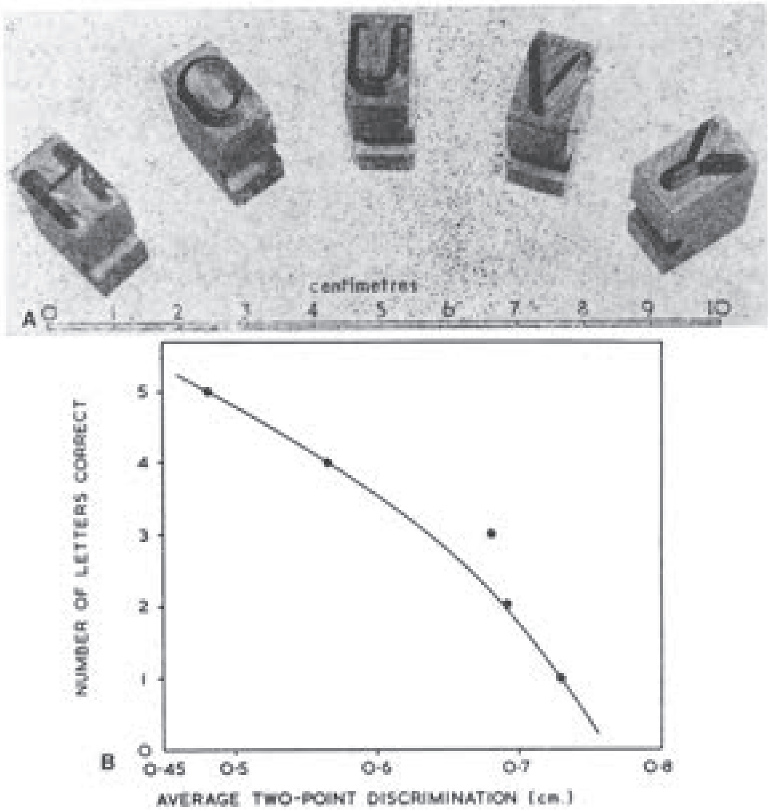


Figure 6.8 Porter's letter test: *A*. The set of five letters*. B*. Correlation of letter identification and classic two-point discrimination in 51 fingertip grafts or flaps. (Reproduced with permission from R. W. Poerter: *BR Med J* 2:927-928, 1986.[36])

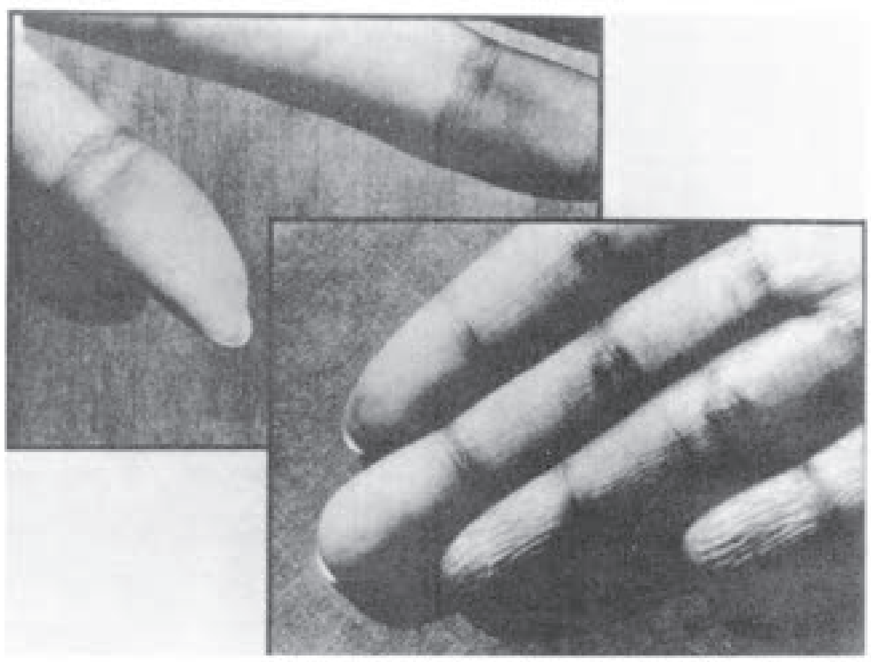


Figure 6.9 Skin wrinkling. Denervated skin, as seen in thumb at *upper left* and index and middle finger at *lower right*, loses the normal ability to wrinkle after emersion in water, as seen in little and ring finger *lower right.* (Reproduced with permission from P E. Phelps and E. Walker: *Am J Occup Ther* 31:565-572, 1977.[38])

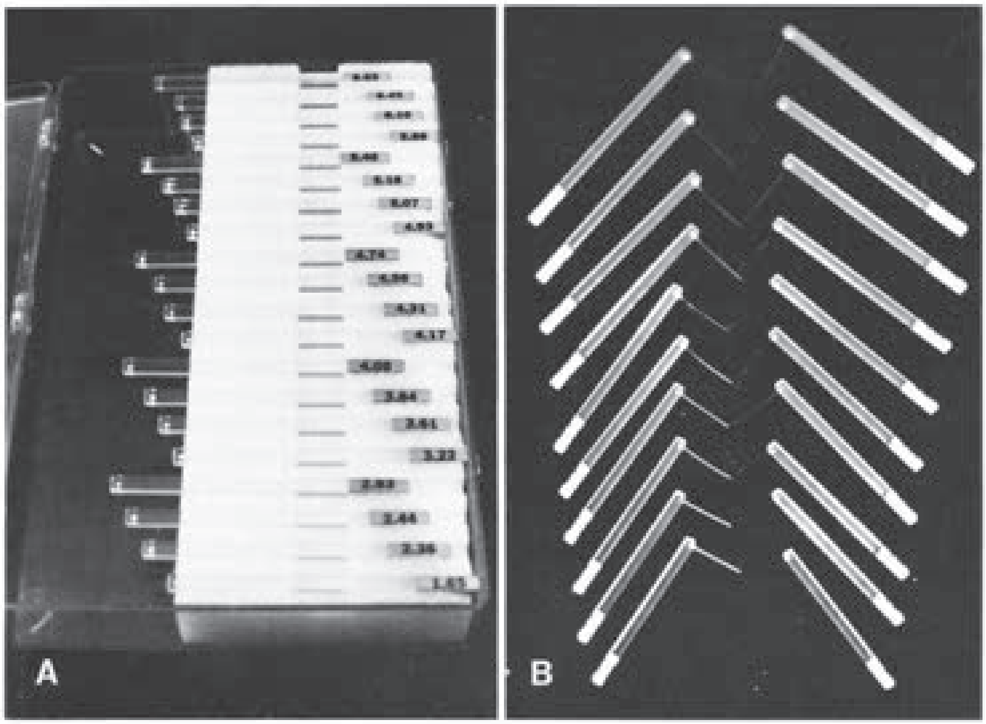


Figure 6.10 Semmes-Weinstein monofilaments for measuring cutaneous pressure thresholds. *A*, Numbers are not the force in milligrams but equal (log(10) F mg). (Note how some filaments become bent with repetitive testing *(B)* invalidating their rating.)

von Frey Hairs (Semmes-Weinstein Monofilaments)

The development of von Frey's "hairs" is discussed in Chapter 1. They remain widely used, widely abused, widely misunderstood and controversial three quarters of a century later. For example, one center considers this test the cornerstone of their sensibility evaluation,[30] while a recent engineering analysis concluded[39]:

> Variations in the buckling stress as high as a factor of eight are difficult to avoid. Gross errors arise from careless application, variations in the elastic modulus due to changes in temperature and humidity, and variations in the attachment of the fibers to handles and differences in the ends of the filaments. Interpreting results for this instrument (Semmes-Weinstein) requires an understanding of factors which can influence those results. Probes are simple to use but easy to misinterpret.

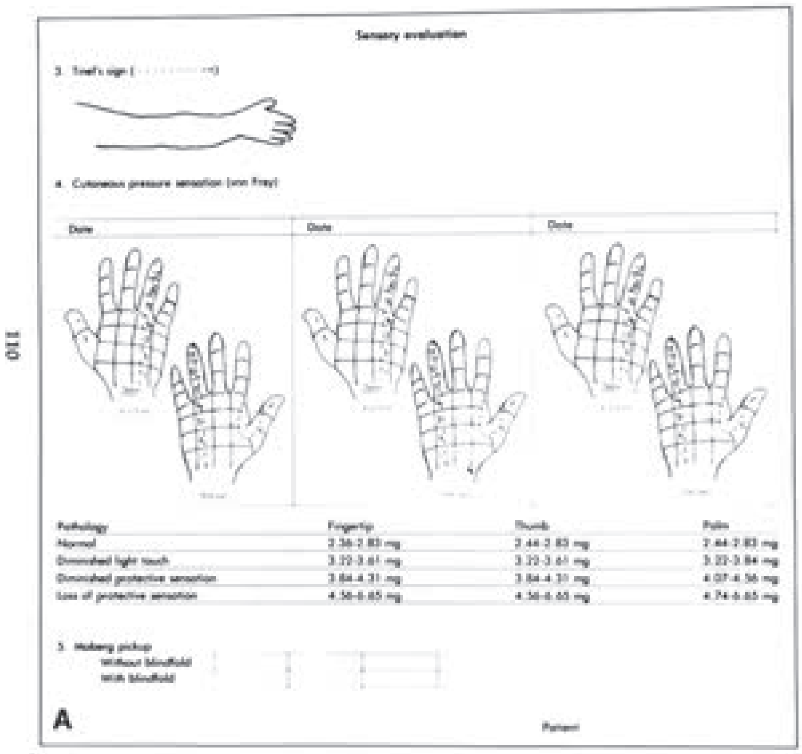
Weinstein[40] introduced the nylon monofilaments as an alternative to using hair. However, although nylon mono filaments are more aesthetic and seemingly more scientific than hairs, the filaments have irregularities in the shape of their contact surface and do not eliminate two problems discussed by Henry Head[41] in 1908. Although the object is to measure cutaneous pressure thresholds, high thresholds, in fact, are perceived not as pressure, but as pain.

Towards the end of our research we received a second set of hairs from Professor von Frey which were useful in measuring the punctate pressure capable of producing cutaneous pain. These so called "pain-hairs" exercise considerably greater pressure than those used for testing cutaneous tactile sensibility, and are graduated by calculating the pressure per unit area (see Table 6.10).[41]

The Semmes-Weinstein monofilaments (Fig. 6.10) are labeled with a numerical mark to 6.65. This number is the log (10 F) where F is force in milligrams. As a further example of how easily this test's results are misconstrued, these numerical markings have been reported as the actual threshold values in grams (Fig. 6.11).[31] Rivers and Head attempted to distinguish the force applied from the stress (force per area) applied (Table 6.10). Levin et al.[39] also calculated these (Table 6.11), and these values were incorporated into her reporting system by Bell[30] (Fig. 6.11). Thus, Bell considers a normal threshold to be less than 0.068 gm. Poppen et al.,[33] however, without stating why, have chosen normal to be less than 1.0 gm.

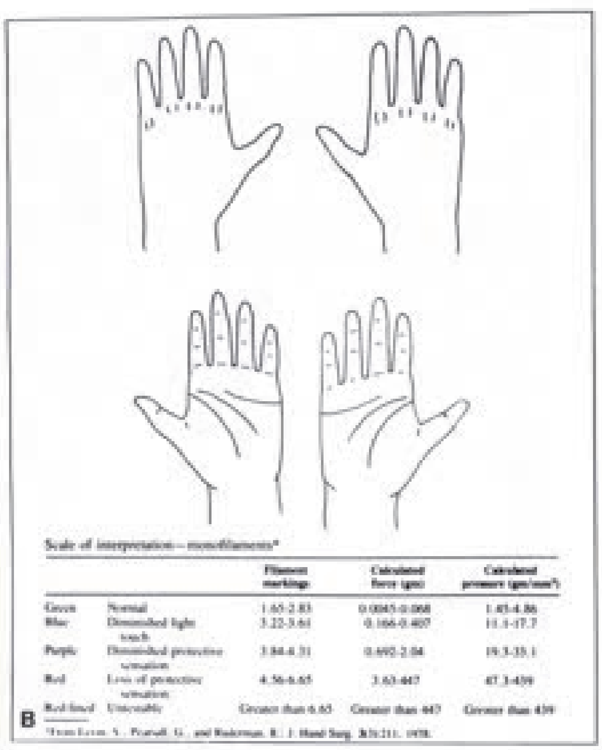
There are at least four problems with the von Frey hair or monofilament type testing: (1) At which point does the upper limit of pressure actually test pain (2) In what terms should the end result be reported, i.e., numerical markings of Semmes-Weinstein monofilaments, force or stress? and (3) Different centers may report different results even using a "fully standardized series of von Frey hairs" (see Table 6.12).[42] In the World War II experience, "two hand centers deviated significantly, one greatly tended to report thresholds of 3 gm and another tended to almost never report thresholds of 50, 39, 10 and 3 gm.[42]

Perhaps the most significant problem with reporting end results of nerve repairs in terms of cutaneous pressure thresholds is that these do no correlate with hand function. This is discussed in Chapter 10 and is illustrated here from the Poppen et al.[33] recent detailed comparisons (Fig. 6.12). This figure from Poppen has the advantage of having included Onne's data.[25] It is clear that for any given cutaneous pressure threshold, the two-point discrimination values range from normal to complete lack of discrimination. For example, a pressure threshold of .75 gm (within normal limits for these authors) is consistent with a classic two-point discrimination of 4 or 32 mm. At 4 mm we could expect normal functional sensation. At 32 mm, we would expect sensations not even sufficient for gross sensory grip.



Pathology	Fingertip	Thumb	Palm
Normal	2.36-2.83 mg	2.44-2.83 mg	2.44-2.83 mg
Diminished light touch	3.22-3.61 mg	3.22-3.61 mg	3.22-3.84 mg
Diminished protective sensation	3.84-4.31 mg	3.84-4.31 mg	4.07-4.56 mg
Loss of protective sensation	4.56-6.65 mg	4.56-6.65 mg	4.74-6.65 mg

Figure 6.11 Semmes-Weinstein end-result reporting. The numerical markings on the instruments are logarithmic values of the force and should not be listed in milligrams *(A)*[31] but rather as correlated with force or pressure *(B)*.[30] (see below)



Scale of interpretation—monofilaments*

		Filament markings	Calculated force (gm)	Calculated pressure (gm/mm²)
Green	Normal	1.65-2.83	0.0045-0.068	1.45-4.86
Blue	Diminished light touch	3.22-3.61	0.166-0.407	11.1-17.7
Purple	Diminished protective sensation	3.84-4.31	0.692-2.04	19.3-33.1
Red	Loss of protective sensation	4.56-6.65	3.63-447	47.3-439
Red-lined	Untestable	Greater than 6.65	Greater than 447	Greater than 439

*From Levin, S., Pearsall, G., and Ruderman, R.: J. Hand Surg. 3(3):211, 1978.

Table 6.10
von Frey Hairs[a]

Number by Which Hair Is Known	Pressure (gm)	Hair Radius (μm)	Hair Area (mm^2)	Radius of Circle of Same Area (μm)	Pressure per Unit Area	Tension
Tactile hairs						
1	0.04	30 × 54	0.005	40	8 gm/mm^2	1 gm/mm
2	0.10	48 × 58	0.009	52	12 gm/mm^2	2 gm/mm
3	0.21	55 × 90	0.015	70	14 gm/mm^2	3 gm/mm
4	0.23	40 × 80	0.011	58	21 gm/mm^2	4 gm/mm
5	0.36	60 × 90	0.017	74	21 gm/mm^2	5 gm/mm
8	0.88	100 × 120	0.038	110	23 gm/mm^2	8 gm/mm
Pain hairs						
35	1.4	100 × 130	0.041	114	35 gm/mm^2	12 gm/mm
70	3.0	115 × 115	0.042	115	70 gm/mm^2	26 gm/mm
100	3.5	80 × 140	0.035	110	100 gm/mm^2	32 gm/mm
150	11.0	125 × 185	0.073	150	150 gm/mm^2	73 gm/mm
266	12.0	115 × 125	0.045	120	266 gm/mm^2	100 gm/mm

[a] Adapted from W. H. R. Rivers and H. Head.[41]

Table 6.11
Stress and Force Calculations and Measurements for a Semmes-Weinstein Pressure Aesthesiometer[a]

Manufacturer's Marking	Calculated Force (F', gm)	Diameter (D, mm)	Area (A, sq m)	Calculated Stress (S', gm/sq mm)	Slenderness (2L/R)	Measured Force (F, gm)	Standard Deviation (oF, gm)	Measured Stress (S, gm/sq mm)	Standard Deviation (oS, gm/sq mm)
6.65	448	1.142	1.02	439	130				
6.45	283	1.033	0.84	337	141				
6.10	126	0.805	0.51	243	180	86.5	4.3	171	16
5.88	76.0	0.732	0.42	181	200	73.2	1.9	175	13
5.46	28.0	0.582	0.27	107	251	22.3	1.5	82.0	9.6
5.18	15.2	0.525	0.22	69.1	280	18.6	0.8	84.9	7.9
5.07	11.8	0.475	0.18	65.6	312	17.0	1.5	94.9	13
4.93	8.53	0.423	0.14	60.9	341	10.6	0.5	76.1	7.4
4.74	5.51	0.322	0.081	68.0	453	3.14	0.07	38.9	2.8
4.56	3.64	0.313	0.077	47.3	473	2.81	0.06	36.6	2.6
4.31	2.05	0.284	0.063	33.1	520	1.85	0.06	29.5	2.4
4.17	1.48	0.244	0.047	31.5	593	1.58	0.06	33.7	2.9
4.08	1.20	0.228	0.041	29.3	650	0.977	0.030	23.9	1.9
3.84	0.693	0.214	0.036	19.3	689	0.562	0.011	15.7	1.1
3.61	0.408	0.171	0.023	17.7	851	0.213	0.004	9.29	0.64
3.22	0.166	0.137	0.015	11.1	1,050	0.112	0.007	7.50	0.84
2.83	0.068	0.132	0.014	4.86	1,090	0.091	0.005	6.52	0.68
2.44	0.0276	0.104	0.0085	3.25	1,400	0.034	0.002	4.02	0.43
2.36	0.229	0.075	0.0044	5.20	1,930	0.0094	0.0001	2.14	0.13
1.65	0.0045	0.063	0.0031	1.45	2,300	0.0040	0.0001	1.29	0.09

Table 6.11 Stress and Force Calculations and Measurements for a Semmes-Weinstein Pressure Aesthesiometer(a) [(a)Adapted from S. Levin et al.[39]]

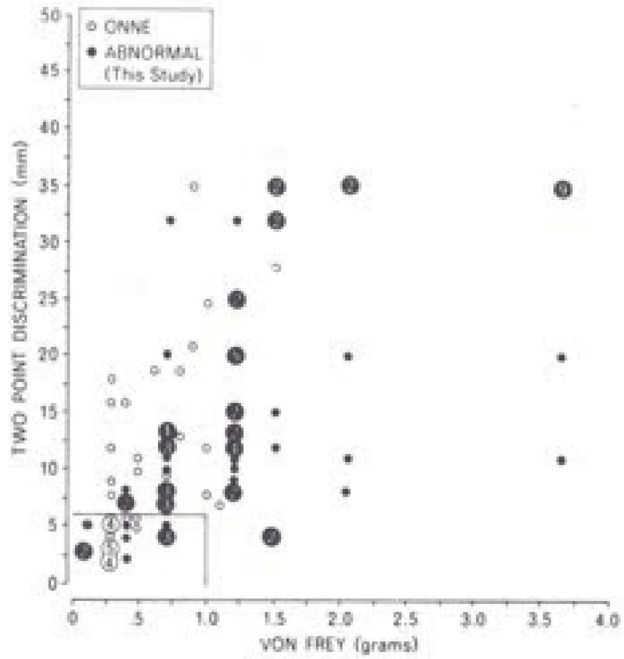


Figure 6.12 Correlation of von Frey and Weber testing after digital nerve repair. Note that for any given von Frey value there is a wide range of two-point discrimination values. Thus, there is no correlation between these two tests. *Black circles* are data from Poppen et al,[33] and *white circles* are data from Onne.[25] The graph is from Poppen et al.[33] The box in the *lower left corner* of the graph represents these authors normal limits (see text). (Reproduced with permission from L Onne: *Acta Chir Scand [Suppl]* 300:1-70, 1962[25] and N. K. Poppen et al.: *J Hand Surg* 4:212-226, 1979.[33])

Table 6.12
Standardized Set of von Frey Hairs Employed at United States Hand Centers during World War II[a]

Hair Number	Threshold
0	>50 gm/mm^2
1	50 gm/mm^2
2	35 gm/mm^2
3	25 gm/mm^2
4	16 gm/mm^2
5	5 gm/mm^2
6	3 gm/mm^2
7	>3 gm/mm^2

[a] Adapted from Y. T. Oester and L. Davis.[42]

I believe that von Frey hairs, or Semmes Weinstein monofilaments, or any new device that measures cutaneous pressure thresholds is severely limited in what it can tell us. Functional sensation depends on a critical number of sensory fibers being present and connected to the appropriate mature receptor. A test that measures innervation density can supply the critical information. A test that determines thresholds alone cannot. Until then I believe that determining innervation density is the most critical clinical test we can do of a given fiber/receptor system.

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Chapter 7

PATTERN OF SENSORY RECOVERY

INTRODUCTION

Following repair of a sensory nerve, the axons regenerate, reinnervate the distal tissue into which they have regenerated, and reestablish connection of the central nervous system with the external world. Are the various sensory submodalities *all* re-established simultaneously or is there a predictable sequence to this recovery of sensation?

One of the classic descriptions of the pattern of sensory recovery is that recorded by Head and his co-workers.[1, 2] Head's own superficial radial and lateral antebrachial cutaneous nerves were divided electively and the resultant sensory defect and pattern of recovery methodically noted. The standard neurologic tests (cotton wisps, pin, hot and cold, pressure) were utilized for the testing. The first returning sensations were unpleasant responses to the usually nonnoxious stimuli, and only extremes of stimuli, like heavy pressure, were perceptible. Head believed a separate population of nerve fibers mediated these sensations and he chose the term "protopathic," meaning "responsive to gross stimuli" for this type of sensibility. With time, the ability to be "more discriminating" returned. Head believed this "epicritic" sensibility was due to a second population of nerve fibers, regenerating more slowly.

In 1934, John Staige Davis, who was the first Chief of the Division of Plastic Surgery at Johns Hopkins[3] and who authored the first textbook of Plastic Surgery in the United States,[4] reviewed published studies of sensory recovery in skin grafts up to that time. The few earlier reports had concluded that "speed of recovery depends upon the type of innervating nerve ... touch, pain and temperature return in the order named after pressure."[5] The earliest observations of the pattern of sensory recovery were made most often in grafted skin and included the sequences (1) pain before touch before temperature[6]; (2) pain before temperature before touch[5]; (3) pain before touch[7]; and (4) pain and sweating contemporaneously before temperature.[8]

Closely related to the observations made on grafted areas, were observations made on areas of normal skin being reinnervated following nerve injury. The classic tests of pain, temperature, cotton wool, and Tinel's sign, were utilized not to establish a pattern of sensory recovery but to attempt to establish rate at which nerve fibers regenerated. Such a rate would enable the clinician to prognosticate, evaluate success of nerve repairs, judge the need for a “second look” or neurolysis, etc. Contemporary teaching is that “nerves regenerate at about 1 mm per day or an inch per month” usually “allowing two to four weeks for delay in crossing each suture line.” Among the most fascinating studies to read are the classics by Seddon et al.[9] and Sunderland.[10] Every conceivable approach to arriving at this information, including sophisticated mathematics and meticulous longitudinal clinical studies following neuropraxia and nerve repair, for motor as well as sensory function, is utilized. Conclusions from their work are that we may never know the actual rate of axonal regeneration, because included in what we can clinically measure are (1) the “initial lag time” related to suture line crossing; (2) the advance of multiple axonal sprouts which may be stimulated (Tinel’s) but are unrelated to functional or anatomic restoration; (3) the end or “terminal lag time” related to re-establishing (or failing to reestablish) the appropriate end organ connection; and (4) the end or “terminal lag time” related to recovery of a sufficiently low threshold of the fiber/receptor system. A series of observations from Seddon et al[9] suggests the following rates:

Tinel’s sign ....advances at 1.71 mm/day
Motor radial nerve ....advances at 1.60 mm/day
Average, “all nerves”.... advances at 1.40 mm/day
Pain ....advances at 1.08 mm/day
Touch ....advances at 0.78 mm/day

In general, rates of recovery have been observed ranging from 1 to 4 mm/ day. The final conclusions from both reviews may be summarized[9, 10] (Fig. 7.1):

1. The rate of sensory recovery may be calculated by measuring the advance of pain and touch sense in a long zone of cutaneous insensibility.
2. The rate of advance of Tinel’s sign is of limited functional significance, but has some prognostic value.
3. The rate of recovery falls off progressively as the process nears completion.
4. The rate of regeneration diminishes as the distance increases between the axonal tips and the cell bodies, and this factor appears to be a variable independent from 3.
5. The factors affecting rate are: (A) the interval between injury and repair; (B) the state of stumps at suture line; (C) the postoperative stretching (suture line tension).

PATTERN OF RECOVERY FOLLOWING NERVE INJURY

On February 3, 1969, I presented a paper entitled “Correlation of Clinical Tests of Sensibility in the Hand with Recent Neurophysiological Evidence” to the meeting of the Johns Hopkins Medical

Society. This was during my 3rd year of medical school. Shortly thereafter, the manuscript was submitted to the *Johns Hopkins Medical Journal* for consideration for publication. On July 30, 1969, the editor of the *Journal* wrote back, rejecting the paper. He wrote that while the manuscript was "an interesting review ... there was no data which might support the opinions of the authors, and therefore, no real contribution was made ..." Reviewers further felt I had "arbitrarily tested two sensory tests out of a dozen or more that might have been more sensitive." I added a series of patient examinations to the paper and resubmitted it in May, 1970. It included six tables and 10 figures and much theorizing. It was accepted pending revisions. After reworking and shortening, it was resubmitted in June, 1971, during my internship. It was accepted. It then contained just one table, six figures, and no theorizing. The paper was entitled "Evaluating Recovery of Sensation in the Hand after Nerve Injury."[11]

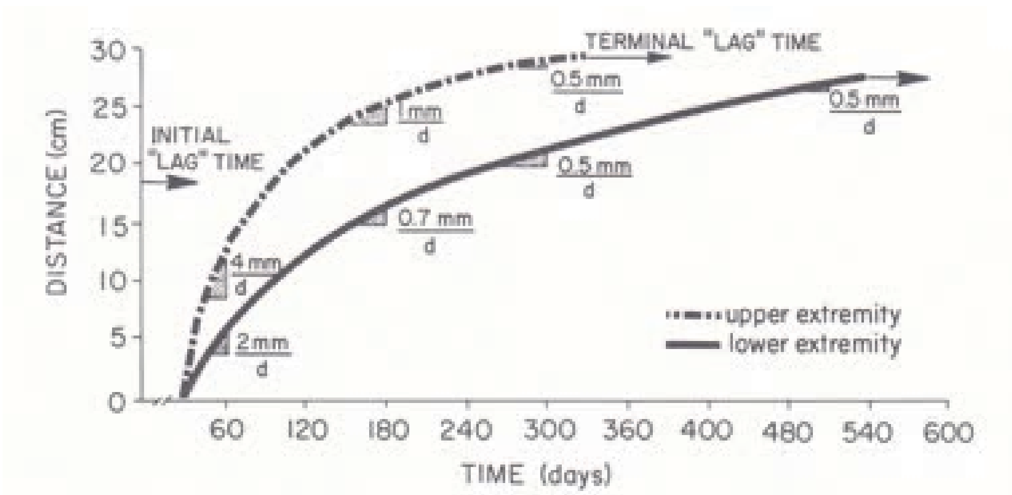

Figure 7.1 Rate of regeneration of peripheral nerve. These are hypothetical curves of sensory recovery in an upper and lower extremity nerve, each repaired about 30 cm proximal to the distal phalanx, with curves being based on conclusion from Seddon et al.[9] and Sunderland.[10] Note: Initial lag time related to suture line crossing, terminal lag time related to attempted re-establishment of end organ connections, and receptor maturation. Due to increased distance of the lower extremity axon tip from its central neuron, its rate of regeneration is everywhere slower than for the upper extremity nerve. For both nerves, the rate of regeneration diminishes as the periphery is approached.

The pattern of sensory recovery was evaluated by serial clinical examinations. Evaluation included finger stroking and pressure with the examiner's finger on the patient's finger to stimulate perception of moving touch and constant-touch, respectively, and tuning forks of 30 cps and 256 cps to stimulate perception of flutter and vibration (see Chapter 10). Twelve patients, six following nerve crush and six following nerve repair were evaluated. Injuries were to median[7], ulnar[2] and median plus ulnar[3] nerves. Following recovery of perception of painful stimuli, a consistent pattern was found for the touch "submodalities": perception that the 30 cps stimuli was the first to recover followed very closely by perception of moving-touch, followed in several months by perception of constant-touch, and finally by perception of the 256 cps stimulus (Fig. 7.2). The entire sequence occurred faster following crush injury than following nerve repair. Also noted in that study and illustrated with a figure (all of which was deleted from the published "edition" of the manuscript) was the orderly recovery of the normal threshold for both moving- and constant-touch: greater force was required with both test stimuli to achieve perception initially than it was later on in recovery; and at the time when greater force was being required to perceive the stimulus at the fingertip, less force was required over the proximal phalanx (Fig. 7.3).

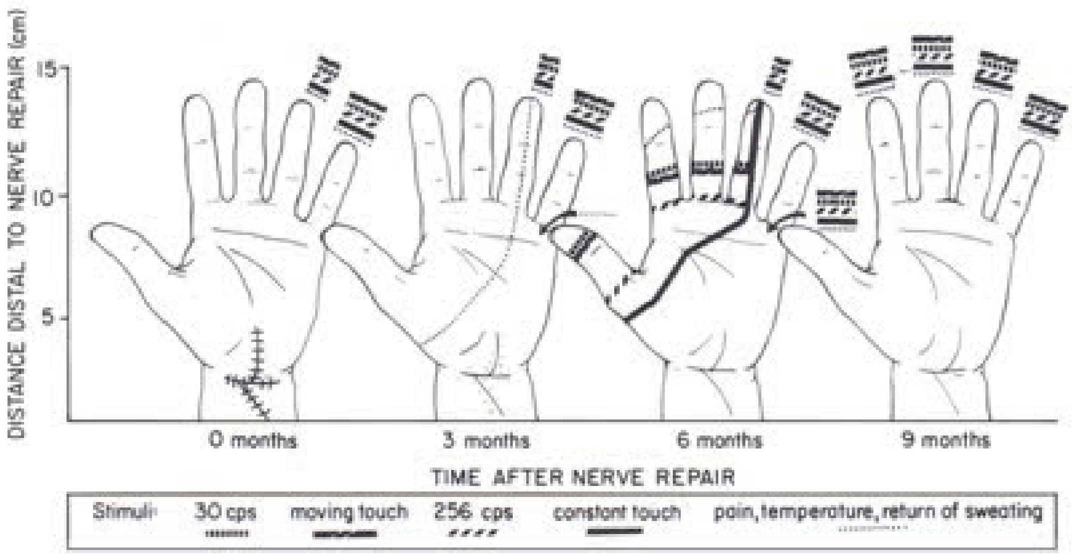

Figure 7.2 Pattern of sensory recovery following nerve injury. An orderly sequence occurs in return of perception of the touch submodalities. This sequence begins after reception of pain and temperature has recovered. As illustrated for a median nerve repair, the first to recover is perception of the 30-cps vibratory stimulus, followed closely by perception of moving-touch. Then, after usually a significant delay, comes perception of constant-touch, and finally the 256-cps vibratory stimulus. (Adapted from A. L. Dellon et al.[11])

The observations were made in that study that (1) patients appeared to improve in their perceptions during the test period, and that (2) deviations from the normal pattern of recovery, i.e., recovery of perception of 256- cps stimulus at the fingertip while perception of constant-touch remained at the palm, represented a "gap" or "failure" to achieve a given sensory potential, thereby laying the cornerstones for the development of sensory re-education (see Chapter 12).

HYPOTHESIS FOR THIS PATTERN

I propose that the basis for the observed orderly sequence of recovery of perception of stimuli in the fingertip following nerve injury (which is, first pain and and to the re-innervation of the sensory receptor, secondarily. Given that the diameter of the unmyelinated C fibers and the thinly myelinated group A delta fibers is of the order of 1 to 2 µm, while that of the thickly myelinated fibers is of the order of 15 to 20 µm, these being the groups mediating perception of pain/temperature and touch, respectively, there is an enormous difference in the volume of axoplasm of the nerve fibers in these two different groups. Following nerve injury, sufficient axoplasm must be produced to fill this axonal volume. Even though a regenerating axon regenerates as a thin axonal sprout, and even though the distal endoneural sheaths contract after nerve division, the total axoplasm required to re-establish continuity with the fingertip after a nerve division at the wrist must be greater for the touch fibers than for the pain and temperature fibers. Little is known about the ability of the dorsal root ganglia neurons, which are the cell bodies of these axons, to produce axoplasm. If we assume that a group A delta neuron can produce axonplasm as rapidly as group A beta neuron, it would take the group A beta neuron longer to produce its required axoplasm than group A beta because it has much more to produce.

For any given length, the volume of a cylinder is proportionate to the square of the radius of the cross-section of the cylinder, V = 1 R(2). For the A delta fiber, for example, radius of a 2 u fiber, is 1 u. For the A beta fiber, the radius for a 20 u fiber is 10 u. The ratio of volumes is therefore $(10^2):(l^2)$ or 100:1.

This hypothesis, which we call the "neuron pump" (Fig. 7.4), explains recovery of pain perception ahead of touch at the periphery on the basis of axoplasm production in a thinner fiber.

I propose that the basis for the observed sequence of recovery of touch submodalities is related to the nature of the sensory end organ. The sequence of 30 cps, moving-touch, constant-touch, 256 cps can be restated in terms of sensory receptor correlation as Meissner corpuscle, Meissner corpuscle, Merkel cell-neurite complex, and Pacinian corpuscle (see Chapter 3). Thus, the close proximity in time, which is often simultaneous, between recovery of 30 cps and moving-touch is explained on the basis that they both required the re-established integrity of the same fiber/receptor system. Recovery of 30 cps ahead of 256 cps relates to the relative ease of reinnervating a Meissner corpuscle compared to reinnervating a Pacinian corpuscle. (The pertinent references to this are discussed in detail in Chapter 5.) One group of investigators[12] believes that failure to clear myelin debris, or a similar "mechanical hypothesis," is the basis for poorer reinnervation of Pacinian corpuscle than Meissner corpuscle. I believe that a possibly more important basis is the intrinsic design of these two fiber/receptor systems. This hypothesis concerns the multiple fiber innervation of a Meissner corpuscle (three to nine axons may enter a single corpuscle) versus the single fiber innervation of a Pacinian corpuscle. Simply put, statistically there is a greater chance for a regenerating quickly-adapting fiber to reinnervate a Meissner corpuscle than a Pacinian corpuscle (Fig. 7.5). I cannot explain more specifically the order of constant-touch between these two extremes except as explained by an extension of the above hypothesis. The axon to corpuscle ratio of Merkel cell-neurite complex is less than one, whereas for the Meissner corpuscle it is greater than one (Fig. 7.5). Merkel reinnervation should occur after Pacinian. There is, however, apparently no mechanical blockage to regenerating slowly-adapting fibers growing beneath intermediate ridges and reestablishing contact with or inducing Merkel cells as there is with the reinnervation of a Pacinian corpuscle. Thus, constant-touch is perceived ahead of the 256-cps stimuli.

An alternative hypothesis regarding the recovery of the perception of constant-touch ahead of 256-cps stimuli may relate to receptor maturation or threshold recovery, rather than reinnervation of receptors, *per se.* Both a Merkel cell-neurite complex and a Pacinian corpuscle fiber/receptor system may re-establish continuity simultaneously, but perhaps the Merkel cell-neurite complex, where one fiber innervates many Merkel cells, reestablishes a lower threshold for stimulation earlier than does the single receptor Pacinian corpuscle.

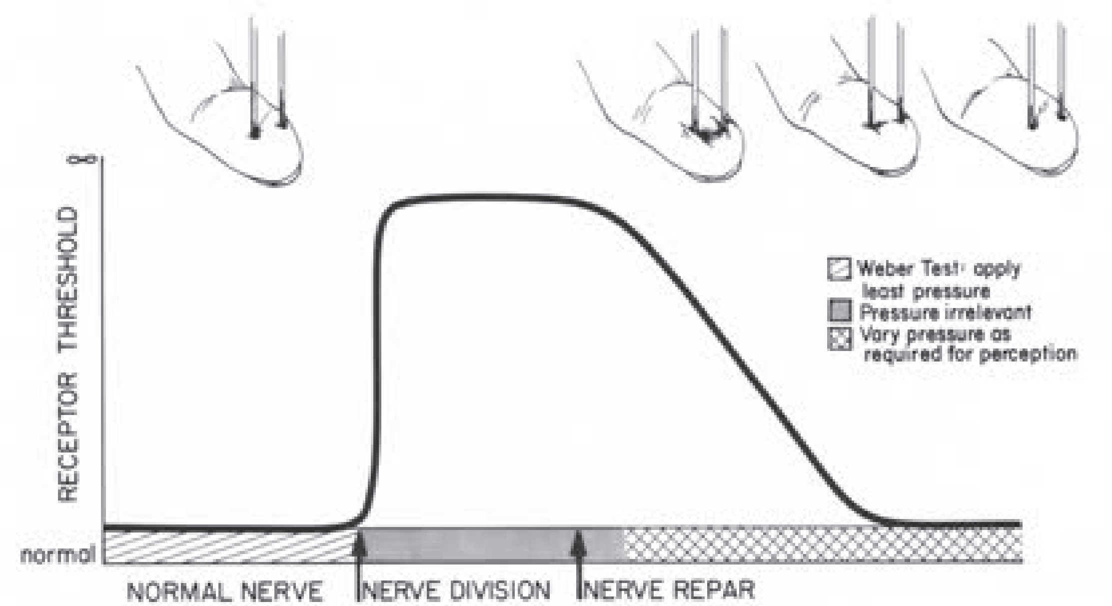

Figure 7.3 Recovery of sensory thresholds. The initial perception of a sensory submodality during recovery requires use of sufficiently high stimulus intensity. With time, the threshold for stimulus perception diminishes.

CLINICAL SUPPORT FOR PATTERN OF RECOVERY

It seemed to take about a decade for the pattern of recovery of touch sub-modalities as described to be disseminated, accepted, tested independently, and corroborated in print. My observations of the pattern described were made in 1969. In 1976, Jabaley et al.[13] reported detailed clinical testing, utilizing moving-, constant-touch, and 30- and 256-cps stimuli. These authors did not report longitudinal follow-ups on individual patients, but rather reported a series of findings on a series of patients at some time after nerve repair. Nevertheless, their observations confirmed my observed pattern in that they found a greater number of patients (13 of 17) able to perceive the 30-cps than the 256-cps stimuli, suggesting that 30-cps perception recovers ahead of the 256 cps. They found essentially the same number of patients (14 of 17) able to perceive moving-touch as 30- cps stimulus, again confirming my observations. They discovered that more patients perceived constant-touch (14 of 17) than 256 cps, again consistent with my observations. It was not possible from a review of their data to determine the relative recovery of moving- and constant-touch with respect to each other.

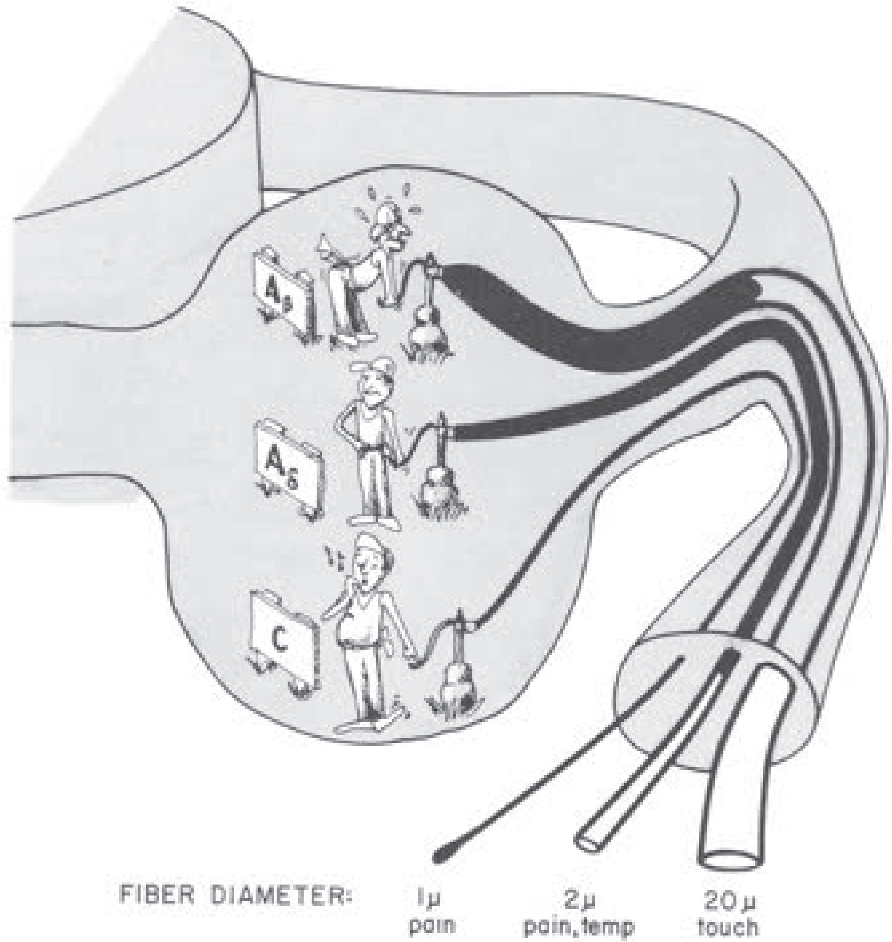

Figure 7.4. Neuron pump hypothesis. Assuming equal ability to produce axoplasm for dorsal ganglia neurons, axoplasm should reach the end of the lower volume, thinner fibers before the end of the higher volume, thicker fibers.

Two other studies have utilized this type of clinical testing in evaluating recovery of sensibility[14,15] These studies report observations consistent with my own.

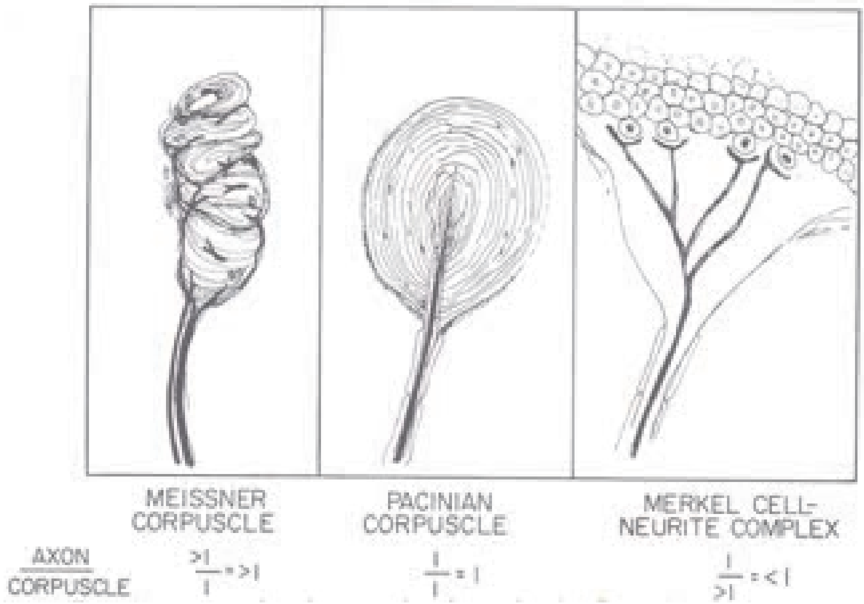

Figure 7.5 Relative ease of re-innervation hypothesis. Based upon observed axon to corpuscle ratios, it statistically should be easiest to reinnervate the Meissner corpuscle, and thus the first perceptions to be recovered are 30-cps vibratory stimuli and moving-touch. Perception of 256-cps vibratory stimuli are last to recover probably because of mechanical obstructions to Pacinian reinnervation and earlier threshold maturation of Merkel cell-neurite complexes.

My observation that once perception of a sensation has recovered, it becomes easier and easier to stimulate, i.e., threshold values are high at the time of initial recovery of the sensory submodality and then decrease with time toward normal, has been observed before[16-18] but not applied to clinical sensory testing. Brown and lggo[16]; studied recovery of threshold in the slowly-adapting cat touchpad fiber/receptor system. After nerve crush, this decreased from a threshold greater than 200 gm to one of 10 gm. Silver et al.[17] devised a “sensory index” based on a voltage threshold for electrical stimulation at a frequency of about 3 cps. They report a longitudinal observation after a median nerve repair of one patient in whom the index changes (threshold changes) as sensory recovery proceeds from proximal to distal. Recently, Dykes and Terzis,[18] in a baboon median nerve crush model, documented a progressive decrease in tuning curves for low frequency rapidly-adapting fibers; that is, at increasingly longer intervals after nerve injury, recordings from peripheral receptive fields demonstrated progressive decreases in threshold. My own observations, over the past decade, have continued to confirm both the pattern of sensory recovery described above and the changing sensory threshold as the fiber/ receptor system matures. Applications of these observations to the clinical evaluation of sensibility are presented in Chapter 10.

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Chapter 8

MOVING TWO-POINT DISCRIMINATION TEST

INTRODUCTION

In the past 2 decades, largely due to the urging of Erik Moberg,[1-5] the hand surgeon has abandoned the neurologist's pin and cotton wool, the goal of which was localization of a lesion within the central nervous system, and has embraced the paper clip, the goal of which is supposed to be measurement of the functional sensibility of the hand. Although the classic Weber "static sensory" two-point discrimination test does correlate with the hand's ability to perform static grips, critical observers have found that this classic two-point discrimination does not always parallel active hand function. Mannerfelt's[6] careful evaluation of skin grafted to fingertips revealed that two-point discrimination did not correlate with function, as judged by the coin test or Moberg's pick-up test. McQuillan[7] wrote that two-point discrimination "is entirely unreliable after nerve repair." Krag and Rasmussen's[8] analysis of neurovascular island flaps revealed that half of the fingertips (with flaps) did well on the pick-up, despite absent two-point discrimination. Parry and Salter[9] wrote that it is a "misconception to assume that two-point discrimination is a meaningful method of assessing stereognosis." As a clue to this paradox, Parry and Salter observed that active movement is fundamental to hand function and that a "static test," such as two-point discrimination is "irrelevant to function." Instead, Parry and Salter use a timed object recognition test (see "pick-up test," Chapter 6) to measure hand function. Narkas[10] also has indicated that two-point discrimination can be present without valid two-point discrimination." Finally, Seddon[11] has written, "It is curious how elements of movement in tactile appreciation have been disregarded."

This series of criticisms of the classic Weber two-point discrimination test and of static tests seems recent. Yet more than a century ago, Silas Weir Mitchell[12] noted these essential criticisms. He wrote in 1877.

In examining the sensibility, too much care cannot be observed, since there is a natural instinct which causes us too use any power of motion we may have in order to press upon and so examine the touching the body … The compass points, which ought to be rounded, … should both come down with equal force and at once, since otherwise the succession of impressions informs the patient there are two points in use … Above all, it is essential … to see that the patient does not move the part during the time of testing it. There seems to be an almost uncontrollable prompting to do this in every instance where the sense of touch is puzzled; and if he be allowed to stir the part ever so little, the answer he will make will often prove correct, when in the absence of motion would have been defective.

The sensation that something is moving across the surface of the fingertips is medated by the quickly-adapted fiber/receptor system (see chapter 3). Tactile gnosis, the ability to “see” with the fingertips, is possible to achieve through a series of discontinuous constant-touches, but this is awkward and inefficient. The natural approach to sensory exploration depends upon a continuous movement of the hand or fingertips. That our central nervous system and mechanisms are most effective when interpreting nerve impulses that vary over time has been demonstrated by the blind, who read most efficiently by moving their fingertips over the raised Braille dots, and by psychophysical investigations developing sight-substitute systems for the blind.[1,13,14] Until recently, however, there was no simple way to measure clinically the innervation density of this quickly-adapting fiber/receptor system.

It seemed to me that a test that could measure the innervation density of the Quickly- adapting fiber/receptor system, if not the entire system of group A beta fibers and their receptors, would be a more valid measurement than the classic test, since the Weber test evaluates only the slowly-adapting fiber/reactor system. Such a new test must involve movement and be quantitative. Possible testing devises included screws with different threads, materials with different textures, graded sandpaper, cloth with varied warps, etc., each of which would require standardizations, trials on normal and nerve injured populations , dissemination of the test results, and, if the test’s validity were accepted, the production of such a sensory tool for use by other clinicians. To be accepted and clinically used, the test instrument would have to be small, inexpensive, and readily available. It became apparent that the classic two-point discrimination test and the ubiquitous paper clip had laid the groundwork for a simple modification of Weber’s test. The moving two-point discrimination test would be a test where the ends of a paper clip were moved across a surface of the fingertip at progressively narrower interprong distance until a two-point limen was reached.[15]

PERFORMING THE TEST

The moving two-point discrimination test is performed with a paper clip that is rearranged to form a testing instrument with two right-angles pointers (Fig.8.10. These pointers may be adjusted so that the center of the tips vary from 2 mm to more than 30 mm apart. Due to the technique of the paper clip manufacture, a metallic barb usually is present on one edge of the paper clip tip (Fig.8.1) The rearranged paper clip must be employed such that this barb is away from, i.e., does not stroke the fingertip surface.[15]

The fingertip to be examined is supported by the examining table or the examiner's hand. The paper clip is moved along the surface of the finger from proximal to distal. Just sufficient pressure is utilized for the subject to appreciate the stimulus (Fig 8.2).

First the patient is oriented to the test. Just one of the two paper clip tips is moved along the finger length and the patient is asked what he perceives to have occurred. He is reinforced by being told "that was one moving point." Next both ends of the paper clip, separated by 5 to 8 mm, are moved along the surface of the fingertip. The patient is questioned again. He is then reinforced by being told "that was two."[15]

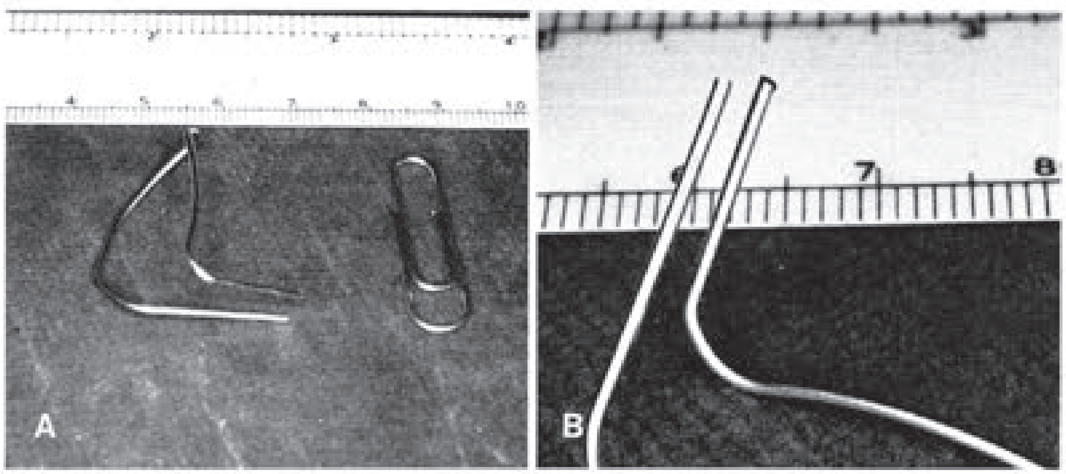

Figure 8.1. The paper clip testing instrument. *A*, The paper clip is bent to form the test instrument. *B*, The process of manufacture results in a barb at the paper clip tip. Care must be taken to avoid stroking the fingertip with the barb. (Reproduced with permission from A. L. Dellon: *J Hand Surg* 3:474-481, 1978.[15])

Next the fingertip is tested, beginning with the two ends 5 to 8 mm apart and proceeding in stages down to 2 mm apart. We do not attempt to measure moving two-point discrimination less than 2 mm. We always begin at a higher value and work down to a lower value to orient the patient to the testing procedure. We always move the paper clip parallel to the long axis of the finger, which generally at an angle to the majority of the "fingerprint ridges."[15]

We randomly alternate the testing stimulus between the one and the two points. If the patient correctly perceives the changes, then we proceed to the next lower value. When the patient begins to answer slowly, and the moving two-point limen or threshold is being approached, we require seven of 10 correct responses before proceeding to the next lower value. Therefore, saying that the moving two-point discrimination of the thumb is 2 mm means that at least seven of the 10 times the patient correctly identified whether the stimulus moving down the surface of the digit was one or both ends of the paper clip.

NORMAL TEST VALUES

The normal value for the two-point discrimination test was found by testing 29 hands in 32 people, ranging in ages from 4 to 83 years. These “normal” people all let active lives, which, for example, meant that one 83-year-old was self- sufficient, cared for her home, and gardened and painted as hobbies. The values are presented in figure 8.3 for the thump pulp of the dominant hand. There was no difference found between the dominant and nondominant hands or between the radial or the ulnar digits. There was no difference related to the patient’s sex. Thus, the normal moving two-point discrimination may be taken as 2 mm in the distal fingertip.

ABNORMAL TEST VALUES

INVALIDS

Does the ability to discriminate diminish if the hand is not used. A clinically form of such sensory deprivation is represented by patients who, through diseases of discomfort in an extremity, fail to use it over a period of time. We studied six such patients; examples of the cause of their limited use are seen in Figures 8.5 and 8.6. Other causes were severe rheumatoid, deformity, chronic alcoholism, osteoarthritis, and hip fracture with associated leg burn. The moving two-point discrimination test values were elevated (abnormal) in all six patients. In patients with disease in each hand, this value was equal bilaterally. In one patient, one hand was immobile and had a moving two-point discrimination of 6 mm, whereas in the other fully mobile hand, the value was 2 mm.[15]

NERVE COMPRESSIONS

In my early investigations with the test, 13 patients with 17 nerve compressions were evaluated.[14] These included 12 median, 4 ulnar, and 1 digital nerve compression. In general, when patients presented with intermittent numbness and tingling, moving two-point discrimination was normal. As degree and duration of compression increased to the point where there was persistent numbness, moving two-point discrimination values increased (became abnormal). These observations were confirmed in a later series of 36 patients with carpal tunnel syndrome.[16] In that series, loss of tactile discrimination was a late finding being proceeded in order by a positive Phalen’s sign, a positive Tinel’s sign, altered vibratory perception (see Chapter 9), and abnormal electrodiagnostic study (prolonged motor latency or antidromic sensory). Whenever the classic two-point discrimination was abnormal, the moving two-point discrimination was also abnormal. However, even a small increase in the value of the moving two-point discrimination test is significant. By this I mean a value of 4 mm for moving two-point discrimination is abnormal and indicates in our clinical and operative correlation intraneural fibrosis. Because the upper limit of normal for classic two-point discrimination is given as 3 to 5 or 4 to 6 mm, an “early” abnormal value is less easy to define. In contrast, the normal value for moving two-point discrimination is 2 mm, and a value of 3 mm is an early abnormal value. Extrapolating the Curtis and Eversmann work,[17] I have considered a moving two-point discrimination value of 4 mm to be an indication for internal neurolysis. Following carpal tunnel release and internal neurolysis, I have observed the abnormal moving two-point discrimination values return to normal.[15, 18]

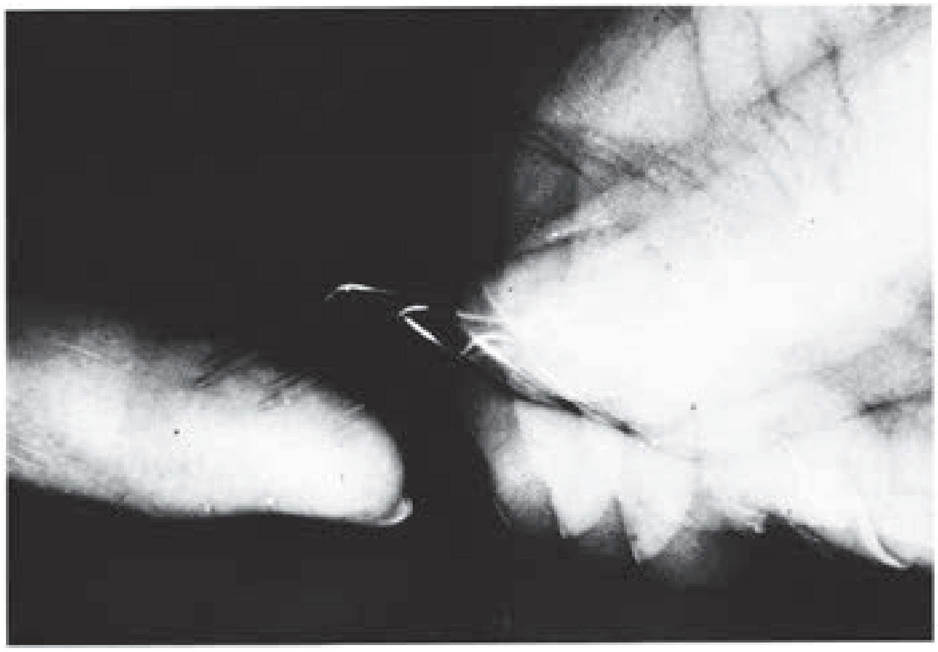

Figure 8.2. The moving two point discrimination test. The two ends of the paper clip are pulled longitudinally from proximal to distal, along the fingertip, and across the papillary ridges. (Reproduced with permission from A. L. Dellon*: J Hand Surg* 3:474-481, 1978.[15])

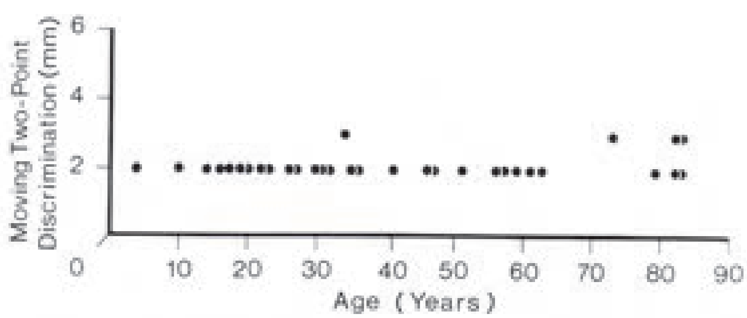

Figure 8.3. Control population. The normal value for the moving two-point discrimination test is 2 mm. There is essentially no change with age.

A word of caution: In my experience, if the moving two-point discrimination is 3 to 4 mm in the thumb and index finger bilaterally, in patients being evaluated for nerve compressions, they have bilateral carpal tunnel syndromes with significant compression. If the thumb, index, and little fingers have values of 3 to 4 mm, there is compression of the ulnar nerve in addition to the median nerve; the ulnar area is usually compressed at the elbow. I confirm this by noting, almost invariably, a difference in sensation between the dorsal ulnar and dorsal radial surfaces of the hand to finger stroking and the 256-cps tuning fork (see Chapter 9). The combination of median nerve compression at the wrist and ulnar nerve compression at the elbow is not rare, especially in the rheumatoid population. (I don't test the middle or ring finger when evaluating ulnar or median nerve problems.)

NERVE LACERATIONS

In patients with complete division of a major peripheral nerve proximal to the palm, there is, of course, complete loss of sensation and therefore no tactile discrimination. However, in patients with a common volar digital nerve division or in patients with digital nerve injury, moving two-point discrimination in the autonomous zone of that nerve was usually 5 to 6 mm and two-point discrimination was usually 7 to 8 mm, depending on the width of the finger, as compared with 2 mm on the uninjured side. If the digital nerve was cut proximal to its dorsal branch, moving two-point discrimination and classic two-point discrimination in the autonomous zone were more than 10 mm.[15] All but the very lightest moving-touch usually could be perceived over the injured autonomous zone while constant-touch could not.

Thus, one of the most common diagnostic errors, sticking a pin into the tip of a finger with a laceration, eliciting a pain response (ouch!) from the patient, and pronouncing the digital nerve "intact," can be avoided by careful tactile discrimination testing. Where the emergency situation doesn't allow this testing to be done (noise, children, uncooperative patient, intoxication, etc.), this diagnostic problem may be solved with the tuning fork (see Chapter 9).

NERVE REPAIR

The patients with nerve repair were evaluated at varying times after their surgery. They each received sensory re- education. When moving-touch and constant-touch perception returned to the fingertip, they entered late phase re-education and had moving two-point discrimination recorded at each subsequent visit. Twenty-three patients were studied.[15] The moving two-point discrimination progressed from near absence, i.e., 12 mm, toward normal over time. Moving two-point discrimination always returned prior to classic two-point discrimination (Fig. 8.4). Moving two-point discrimination was usually 12 mm, 2 to 5 months before classic two-point discrimination was 30 mm. When the moving two-point discrimination had recovered to the 5 to 8 mm range, two-point discrimination usually was in the 15 to 25 mm range. In those patients in whom sensibility returned nearly to normal, moving two-point discrimination reached 2 to 4 mm anywhere from 2 to 6 months before two-point discrimination reached 5 mm (Figs. 8.5 and 8.6). In two patients, the two-point discrimination never progressed below 8 mm, whereas the moving two-point discrimination was 2 or 3 mm. Those cases where moving two-point discrimination recovered to normal just 2 months ahead of two-point discrimination were in patients under 16 years of age. In every patient, as the moving two-point discrimination improved, hand function, as judged by patient opinion, observation of wear marks, and direct examination, improved too. By the time moving two-point discrimination was less than 5 mm, patients could, assuming motor function permitted, perform all of their usual activities (see Chapter 10).

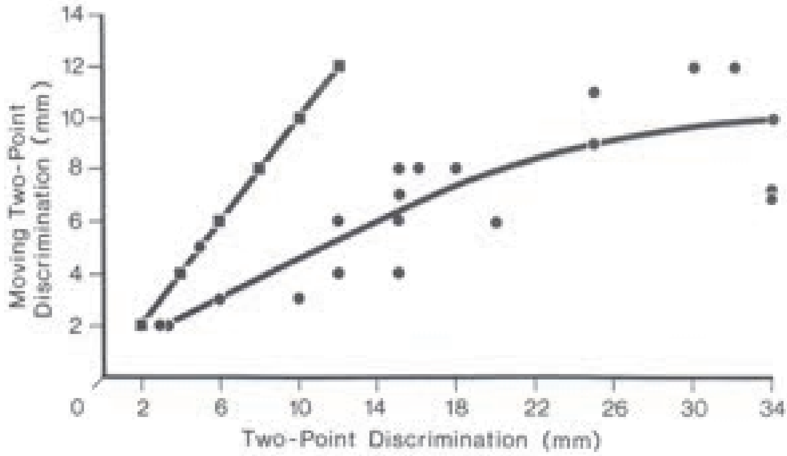

Figure 8.4. Recovery of classical and moving two-point discrimination. The fitted curve of observations (black dots) is below and to the right of the hypothetical curve (black squares) in which classic equals moving two-point discrimination. This indicates that during sensory recovery following nerve repair, moving two-point discrimination always is less (in mm), i.e., better discrimination than classic two-point discrimination. (Reproduced with permission from A. L. Dellon: *J Hand Surg* 3:474-481, 1978.[15])

CENTRAL NERVOUS SYSTEM CORRELATES

The "homunculus," image stretched across the postcentral gyrus, is well-accepted as the organization of the somatosensory cortex. Within the hand area are two smaller areas which receive input from the cutaneous receptors and which differ histologically in their cytoarchitecture. Brodmann's area 1, on the rostral surface of the postcentral gyrus, and area 3, within the sulcus on its posterior wall, have been mapped with microelectrodes.[19] In area 1, 95% of the fields are quickly-adapting, whereas in area 3, 55% of the fields are slowly-adapting. Since a direct relationship exists between the stimulation of a quickly-adapting first order afferent (in the fingertip) and the eliciting of a quickly-adapting response in the sensory cortex,[20] I suggest that the brain has evolved an area differentially receptive to the perception of moving-touch stimuli. I suggest that Brodmann's area 1 primarily would receive sensory input generated by moving stimuli or the fingers moving about an object, whereas Brodmann's area 3 primarily would receive sensory input generated by objects in constant contact with the fingers and pressure.

This submodality segregation should also be present in the spinal cord, linking the specific sensory fiber/receptor systems of the fingertip to the cerebral cortex. Indeed, using precise recording and dissection techniques, this fiber sorting has been identified in the spinal cord.[21,22]

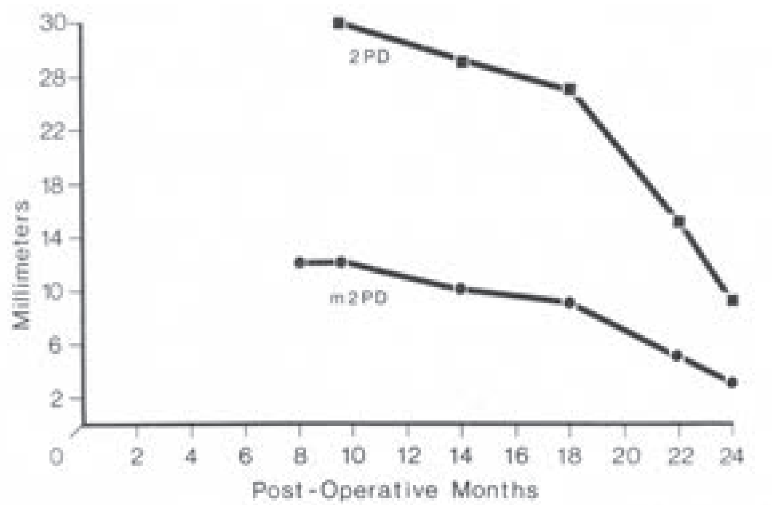

Figure 8.5. Clinical course. A 35-year-old man with primary repair of median nerve. Sensory re-education was given. Note: Moving two-point discrimination recovery was earlier and better than classic two-point discrimination. (Reproduced with permission from A. L. Dellon*: J Hand Surg* 3:474-481, 1978.[15]).

POST-OPERATIVE MONTHS

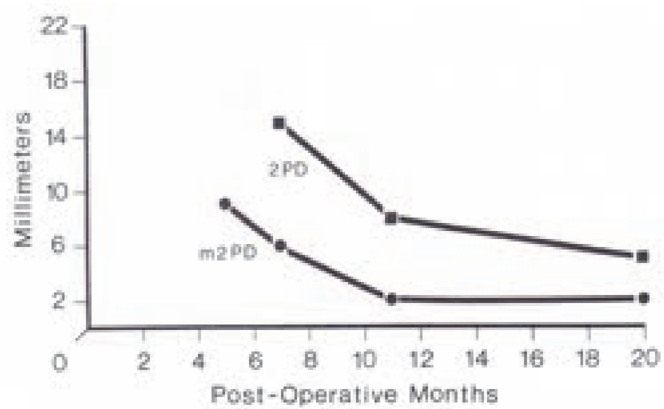

Figure 8.6. Clinical course. A 17-year-old girl with primary repair of ulnar nerve. Sensory re-education was given. Note: The moving two-point discrimination recovery was earlier and better than classic two-point discrimination. (Reproduced with permission from A. L. Dellon: *J Hand Surg* 3:474-481, 1978.[15]).

My statement that the moving two-point discrimination test measures the innervation density of the quickly-adapting fiber/receptor system implies that this fiber/receptor system is capable, in neurophysiologic terms, of making fine discriminations. In 1967, von Prince and Butler[23] carefully studied patients following peripheral nerve repair and noted that even in the absence of classic two-point discrimination (low innervation density of the slowly-adapting fiber/receptor system), patients could distinguish textures, such as grades of sandpaper. In 1968, Vallbo and Hagbarth,[24] using percutaneous recording of peripheral nerves in awake human subjects, demonstrated increased quickly-adapting activity in response to increased roughness of a moving textured surface. In 1969, utilizing fine oscillators to stimulate the quickly-adapting fiber/receptor system, Bach-y-Rita's group[25] found what I would consider to be a moving two-point discrimination of 11 mm in comparison to the classic two-point discrimination of 78 mm. Thus the back, traditionally an area where static touch localizing ability is poor, could be utilized as a vision sensory substitute system with moving touch.

Perhaps the most sophisticated central nervous system correlates come from a series of studies by LaMotte and Mountcastle. In 1975,[26] they reported results of their investigation into the psychophysical ability of two primates, monkey and man, to discriminate fine differences in the sense of flutter-vibration. Both monkeys and humans were trained in amplitude and frequency discrimination to mechanical sinusoids (precise tuning forks). Subjective responses were obtained from the humans, while direct recording from the hand area of the postcentral gyrus (Brodmann's area 1) was obtained from the awake monkeys. Monkeys responded by opening or closing a microswitch adjacent to the forefinger of the stimulated hand: correct response activated a "reward" of apple juice.

Johnson had already demonstrated[27] that the Meissner afferents, those responsive to low frequency vibration had peripheral receptive fields of 1 to 2 mm and good frequency discrimination (in contrast to the Pacinian afferents, high frequency responsive, which have large receptive fields and poorer spatiotemporal patterning). Johnson suggested that the peripheral neural code (the pattern of neural impulses) for intensity (amplitude of the oscillation, "loudness of the vibration") is a spatial one, the number of actively responding Meissner afferents. This differs from the slowly-adapting system, where the neural code for intensity (pressure of the constant touch) is frequency of impulses generated in the single nerve.

LaMotte and Mountcastle,[26] in their psychophysical studies, extended Johnson's observation. Monkeys and men were comparable in the ability to discriminate between mechanical sinusoids differing in amplitude and frequency. That is, both species could detect differences in low frequency vibration when those differences were either in the "loudness" of the vibrations or in their "pitch." Further, the detection system was exquisitely sensitive, being able to detect even very small differences in either of these qualities (differences of just 8 dB for amplitude or 1.8 Hz for frequency). They concluded that the ability to make subjective estimates of magnitude (amplitude) or frequency of these (moving) stimuli was based on spatial and temporal distribution codes, patterns of neural impulses that reflected the overall activity in the relevant neural population (the innervation system).

Utilizing a spatially textured stimulus, wire-wound cylinders of varying turns or nylon fabrics varying in weft and warp in a dual species psychophysical study, similar to that outlined above, LaMotte made the following observations. Movement of the wire-wound cylinder so that the movement of the fingertip pad back and forth along the cylinder length placed the transversely organized papillary ridges (fingerprints) parallel to the wire striations produced a sensation of vibration and texture. Discrimination of a difference of just 1.2 turns/cm was possible. If the fingertip moved in a direction perpendicular to the cylinder length, this discrimination wasn't possible. With the nylon yarns, lower yarn counts (a more open weave) were judged rougher and correlated with discharge rates of the Meissner afferent population. Thus, we see the ability of the quickly-adapting fiber/receptor systems to make fine discriminations where there is a high innervation density.[28]

In their most recently reported study,[29] LaMotte and Mountcastle ablated portions of the parietal cortex (postcentral gyrus) of monkeys previously trained in the above mechanical sinusoid discrimination. That ability to discriminate temporal-spatial patterning (movement) was lost following the ablation. This confirmed earlier clinical correlations between loss of tactile gnosis and loss of the middle third of the postcentral gyrus.[29,30] In the first of these earlier studies,[30] 73% of patients with cortical lesions invading the postcentral gyrus could not identify common household objects (comb, bottle cap, key, spoon, pencil) with their contralateral hand.

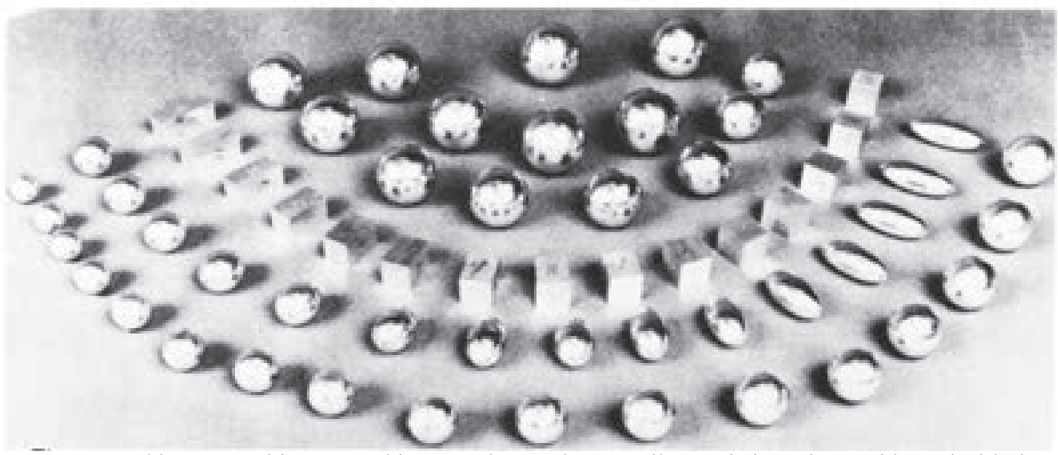

Figure 8.7. Object recognition. Test objects used to evaluate tactile gnosis in patients with cortical lesions. (Reproduced with permission from P. E. Roland: *Arch Neurol* 33:543-550, 1976.[31])

The more recent clinical study[31] attempted to define this loss of "tactile recognition," which, of course, is tactile gnosis, with a precisely defined object recognition test (Fig. 8.7). Ability to correctly identify these geometric shapes was correlated with the mapped cortical defect. Eight patients had significant impairment of this object recognition for each of the three sets of shapes, and each of these patients had a cortical defect invading the postcentral gyrus in its anterior and middle-third (Brodmann's area 1) (Fig. 8.8).

I propose that just as the Meissner corpuscle was the most recent sensory end organ to evolve (see Chapter 2), the specialization of Brodmann's area 1 for tactile gnosis is the most recent central manifestation of sensory evolution. Tactile gnosis depends upon movement detection. The moving two-point discrimination test, the most recent test of sensibility to evolve, determines the peripheral innervation density of this quickly-adapting fiber/receptor system.

CHORAESTHESIA AND THE PLASTIC RIDGE

The quest to quantify sensibility in a way that correlates with hand function better than the classic two-point discrimination test has led Poppen et a1.[32] to conduct an extensive clinical trial with a "new" test instrument, the Plastic Ridge Device (Figs. 8.9 and 8.10). Their study was exceptional in that detailed evaluations of sensibility were conducted on a large number of patients[63] such that Semmes-Weinstein monofilaments, the Weber test, and the Plastic Ridge Device could be compared. In essence, they concluded: (1) von Frey hairs were the least predictive of a patient's tactile gnosis, and the results of von Frey testing correlated with neither the Weber test (see Fig. 6.12) nor the Plastic Ridge Device (see Fig. 8.11) and (2) the Plastic Ridge Device is better than classic two-point discrimination in detecting the presence of tactile gnosis (Fig. 8.12).

I have included the Plastic Ridge Device in this chapter because critical to its use, and essential to what it is testing, is the element of movement. The Plastic Ridge Device is a modification of Renfrew's "depth sense aesthesiometer."[33] The Plastic Ridge Device is moved across the area to be tested parallel to the longitudinal axis of the finger, at a rate of 10 cm in 10 seconds. The patient states when he perceives that something smooth is no longer moving across his fingertip. The Plastic Ridge Device is calibrated transversely in centimeters along the length of the ridge. The line passing the test site at the time the patient states his altered perception is taken as the recorded value for the device.

The observations of Poppen et a1.,[32] I believe, reinforce my impression that the ultimate test of tactile gnosis must be one that evaluates the quickly-adapting fiber/receptor system, i.e., incorporates a moving stimulus. After the appearance of their paper in May of 1979, I wrote a letter to the Editor of the *Journal of Hand Surgery*, which said, in part[34] ". . . (The observations of Poppen et a1.[32]) are those we would have predicted based upon the neurophysiology of the involved nerve fiber/receptor systems."

The von Frey test tells us (conceptually) the threshold required to stimulate a slowly-adapting fiber/receptor (group A, beta/Merkel disc). The Weber test tells us the innervation density of this slowly-adapting fiber/receptor system. Thus a small number of these fibers may have regenerated to the fingertip, reinnervated the appropriate receptors, and "matured" so that, at five years after repair, a low threshold (normal von Frey) might have resulted, but the number of fibers having regenerated might have been too few, i.e., a low innervation density, to give a normal Weber test. The dynamic plastic ridge device requires movement of the (device). Therefore, the test evaluates moving touch, which is mediated by the quickly-adapting fiber/receptor system (group A, beta/Meissner and Pacinian corpuscles). This is an entirely different fiber/receptor population, and therefore one would not expect the results of the von Frey or Weber (static) tests to correlate necessarily with those of this new dynamic test.

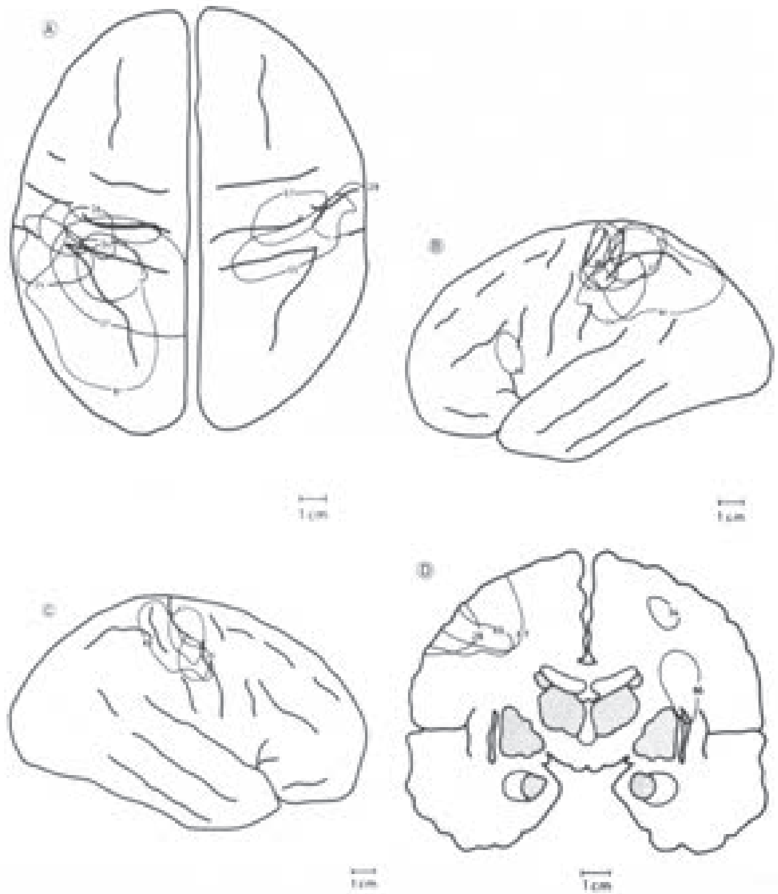

Figure 8.8. Cortical lesions correlating with absent tactile gnosis. Eight patients with significant impairment to recognize geometric shapes with their contralateral hand had these cortical defects in the anterior middle third of the postcentral gyrus (Brodmann's area 1). Section D, through the central sulcus, demonstrates that only four of the eight patients (Nos. 26, 69, 67, 34) had lesions that extended to area 3.[31])

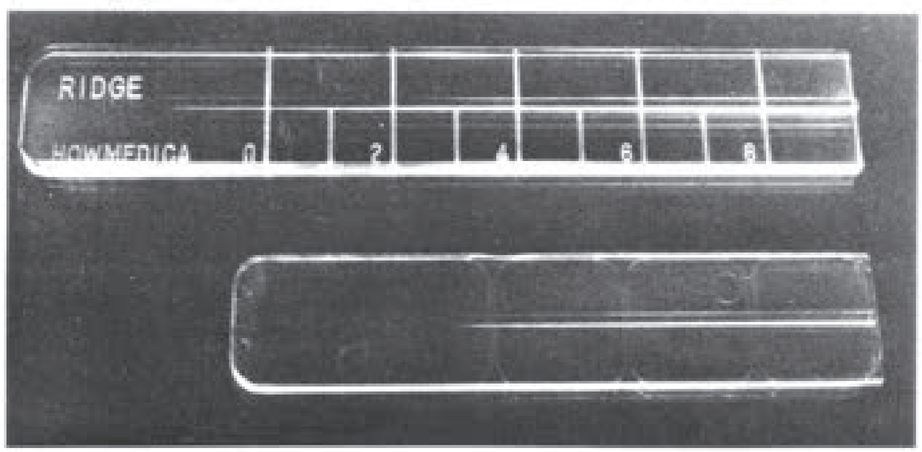

Figure 8.9. Plastic Ridge Device. See text. (Reproduced with permission from N. K. Poppen et al.: *J Hand Surg* 4:212-226, 1979.[3])

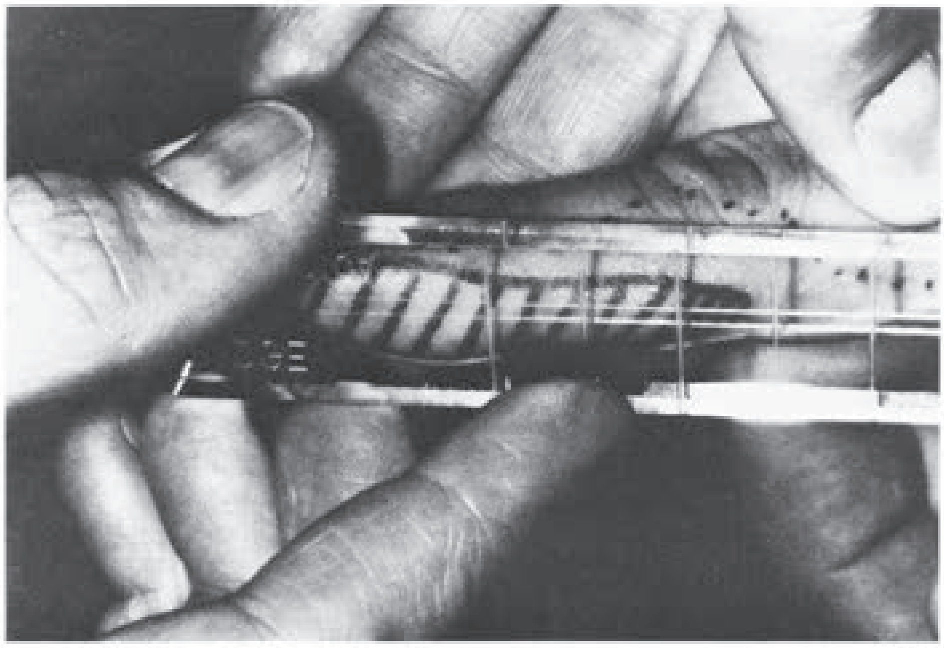

Figure 8.10. Plastic Ridge Device testing technique. See text. (Reproduced with permission from N. K. Poppen et al.: *J Hand Surg* 4:212-226, 1979.[32])

The principle behind the correlation of the plastic ridge test with tactile gnosis is identical to the principle behind the moving two-point discrimination test. Both tests evaluate the same fiber/receptor system.

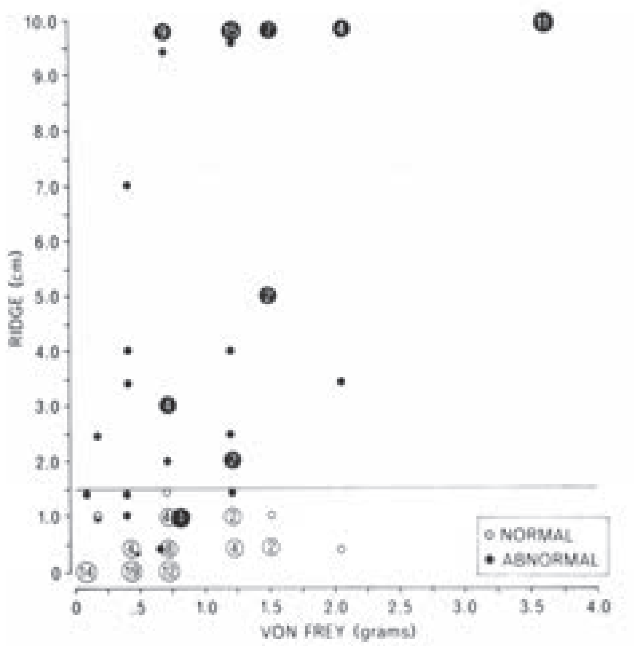

Figure 8.11. Relationship of Plastic Ridge Device and von Frey testing. There is no correlation between the results of these two testing techniques. For a given von Frey value, e.g., 0.75 gm, there is a wide range of Ridge values, e.g., 0.0 to 10.0. For a given Ridge value, e.g., 10.0, there is a wide von Frey value, e.g., 0.5 to 4.0 gm. (Reproduced with permission from N. K. Poppen et al.: *J Hand Surg* 4:212-226, 1979.[32])

There are, however, theoretical and practical problems with the Plastic Ridge Device. In their reply to my Letter to the Editor,[35] Poppen and McCarroll attempted to give the Plastic Ridge Device legitimacy, not by relating it to the known neurophysiologic basis of peripheral sensibility (see Chapter 3), but by relating it to the "somatic sense of space" ("choraesthesia") and to "space detection" instead of "gap detection." This is unfortunate. They cite the "tenfold increase in sensibility judgment made on the basis of overall dimension (disc threshold) when compared to gap detection (measured by disc-annulus or classic two-point discrimination) reported by Vierck and Jones.[36] It is true that Vierck and Jones found that their four normal subjects could detect differences in overall size between test objects (4 to 24 mm in diameter) pressed onto their forearms with a detection threshold of 2 to 6 mm. The classic two-point discrimination in this area was 25 to 35 mm. However, the purpose of that study was to develop a system to test areas other than the fingertip.[36]

Support for the Plastic Ridge Device on the basis that it measures the "somatic sense of space" suffers from the same criticism as the development of the Palesthesiometer to measure the vibratory sense. There is no vibratory sense! Simply because someone demonstrated that (1) vibration can be perceived and (2) a central nervous system lesion can abolish that perception, a unique sense distinct from all others, warranting a name with a Greek prefix, has not been shown to exist. As is expounded in the next chapter, "pallesthesia" is mediated by the quickly-adapting fiber/receptor system. In 1960, Renfrew and Melville,[37] largely on a philosophical or introspective basis, and certainly without any direct neurophysiologic research, postulated the existence of the "somatic sense of space." Having postulated it, they named it Choroesthesia." This does not prove its existence as a unique "sense." They attempted to distinguish the ability to perceive space changes occurring in a plane at right angles to the surface of the finger from space changes occurring in a plane parallel to the surface of the finger. As an example of the type of distinction they attempt to make regarding space, consider the following:[37]

> Should a man look down a deep hole in the ground his statement that he can see the hole could be countered by the suggestion that since his retinal receptors are not stimulated, he does not really see the hole but only the ground around it, that is, he is permitted to see light space but not dark space.

Renfrew and Melville go on to discuss Kant's view of space, debate Realism and Idealism, and finally write "we have worked on the basis that a dermal touch feeling and a dermal space feeling are two different feelings. Our justification for this is based on introspection." They finally, although concluding the opposite, demonstrated direct correlation between their measured space sense and surface sense thresholds. They noted that space sense was lost with lesions of the parietal lobe and posterior spinal columns. They closed the paper with "speculation" as to the sensory receptors for this "sense": they thought these might be the Meissner corpuscle.[37]

TWO POINT DISCRIMINATION (MM)

I believe that choraesthesia, as such, is nonexistent. Tactile gnosis depends upon a profile of neural impulses peripherally generated at the fingertips as the fingertips move about, around, and over the object being recognized. These impulses reach the association cortex as they reach the conscious level, and thus, an identification is made. We must develop instruments that allow simple, unambiguous measurement of the group A, beta fiber's innervation density. The test instrument must be readily available, inexpensive, and understandable.

The Plastic Ridge Device has practical problems. For example, for more than a year I have been unable to obtain one to carry out my own series of studies with it! Once produced, it may become available in the hand center. Certainly it will not be as ubiquitous as the paper clip. Its calibration is a problem. You read it in centimeters of length, but it is really measuring how deeply the ridge goes into the pulp in millimeters!

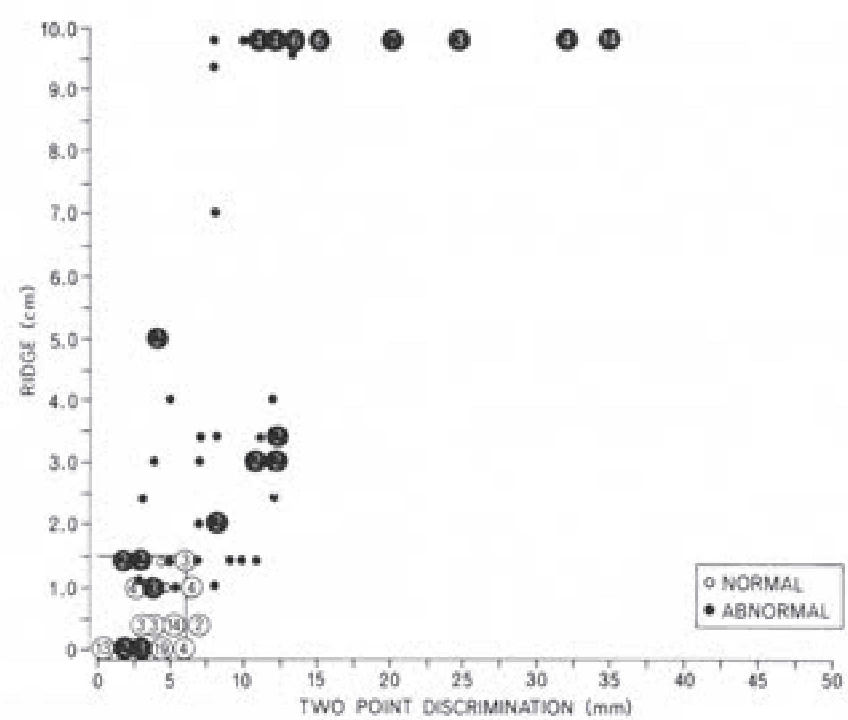

Figure 8.12. Relationship of Plastic Ridge Device and classic two-point discrimination testing. There is no correlation. For a given classic two-point discrimination value, e.g., 7mm, there is a wide range of Ridge values, e.g., 0.5 to 10.0. For a given Ridge value, e.g., 10.0, there is a wide range of discrimination, e.g., 7 to 35 mm. (Reproduced with permission from N. K. Poppen et al.: *J Hand Surg* 4:212-226, 1979.[32])

The Plastic Ridge Device consists of an inclined plane which arises from a smooth surface at one end of the block of plastic (taper equal 1.5/100) to attain a height of 1.5 mm. at the other end (the 9.5 cm.

mark on the linear scale). The ride values of 0.5, 1.5, and. 2.5 cm. on the linear scale correspond to ridge heights of 0.15, 0.30 and 0.45 mm., respectively.[35]

Thus, one reports a value of 1.5 cm, which sounds like a poor result, but which really means a ridge height of 0.30, which is, of course, good. The state of sensibility evaluation is confused enough without a calibration that doesn't read out in terms of what is actually measured!

A real source of error in the use of the Plastic Ridge Device is determining the end point. To be sure, one examiner over time will give reproducible readings. But how fast does one move the device? If we move at 1cm/sec, as suggested, and the patient takes some time to appreciate what he is feeling, and then more time to verbalize it, the calibration on the device has moved past the point at which the threshold was reached! So, a patient says "Now." You look at the device, and the 2.0-cm line is over the area. Now if you move the device faster there will be even more discrepancy between the recorded "ridge value" and the true "ridge depth" that was the threshold.

Furthermore, if the device isn't held flat, the patient will feel two moving edges; the ridge and the horizontal surface of the test device. This, rather than ridge depth, may cause him to respond. How hard do you press? If pressure is constant, the ridge will move along at the same depth! So you must increase pressure constantly as you move. Thus, stimulus intensity is also changing.

An additional practical limitation of the Plastic Ridge Device is using it on someone with a flexion contracture, for example, after combined tendon and nerve injury.[38]

Perhaps the most significant criticism of the study on the Plastic Ridge Device is the summary statement "... The Plastic Ridge Device detects the presence or absence of tactile gnosis in patients in the intermediate range of (classic) two-point discrimination between 8 and 12 mm."[32] Tactile gnosis was never tested in that study. No specific functional testing or correlations, i.e., with the pick-up test or object identification, were performed!

In summary I believe the data reported by Poppen et a1.[32] support my general thesis, in terms of correlating sensory tests with the underlying neurophysiologic mechanism, as outlined above and in more detail in Chapter 10. I believe their study's theoretical basis, the "somatic sense of space," is most probably wrong. I believe the Plastic Ridge Device, when used by an experienced sensory tester, will give results that will parallel those of the moving two-point discrimination test. I am convinced that the lack of availability of the device, the confusion surrounding its calibration, the wide range of normal, and the potential pitfalls in its use will greatly limit its general acceptance.

CLINICAL IMPLICATIONS

The moving two-point discrimination test can determine the capacity of the hand to discriminate moving-touch stimuli.[15] Diminished function is detected early in nerve compression syndromes.

Diminished sensation is detected in the finger with a lacerated digital nerve. Recovery of sensation is detected following release of nerve compression and following nerve repair.

The moving two-point discrimination test is easy to perform rapidly with equipment available virtually everywhere: a paper clip.

The moving two-point discrimination test offers several advantages compared to the classic two-point discrimination test. As the sensation of moving touch is recovered distally sooner than constant touch[8] (see Chapter 7), so too, moving two-point discrimination testing will give information concerning the results of nerve repair sooner than two-point discrimination testing. In the individual patient, the ability to discriminate two-points moving from one recovers not only sooner but also to a higher degree (lower moving two-point discrimination) than does constant-touch (Figs. 8.5 and 8.6). Therefore, if just classic two-point discrimination is tested, the individual's actual and potential sensory recovery are underestimated (Fig. 8.4). Expressed another way, the patient has a better functional result from his nerve repair than classic two-point discrimination testing suggests. The moving two-point discrimination test also is an accurate monitor of gains in function during sensory re-education.

Another advantage of the moving two-point discrimination test is that it is a "pure" sensory test. Moberg's pick-up test and Parry's timed recognition test depend on motor function; the sensation produced depends upon the motor system to manipulate the fingertips in moving-touch. The moving two-point discrimination test, a test done to not by the patient, permits the tester to assess purely sensory function.

Because the moving two-point discrimination test evaluates the fiber/receptor system that mediates moving touch, the moving two-point discrimination test overcomes the criticisms[6-11] of classic two-point discrimination in evaluating functional sensation. If the hand function to be predicted or correlated is purely a static one, i.e., precisely gripping a needle, then the two-point discrimination test will suffice. But if the sensory grip in fact requires movement, such as winding a watch or buttoning a button, or if the hand function requires the fingertips to move over an object, then the moving two-point discrimination test should be more appropriate. Recently, we have demonstrated that the moving two-point discrimination test is the only test of sensibility to correlate with the ability to recognize objects (tactile gnosis) (see Chapter 10).[39]

I propose a hypothesis to explain why the results of nerve repair as judged by classic two-point discrimination are so bad (see Chapter 11. Less than 1% of adults with median or ulnar nerve repairs at the wrist recover to level S4.), and why the moving two-point discrimination recovers sooner and to a better degree (Fig. 8.4). The critical components of this hypothesis relate to (1) the relative scarcity of slowly-adapting fibers (only about one-third of the group A beta fibers are slowly-adapting (see Chapter 3) and (2) the relative scarcity of slowly-adapting fibers to the Merkel cell (axon to receptor ratios are

Meissner >1; Pacinian = 1, Merkel <1, see Fig. 7.5). Thus, following a nerve repair, the absolute number of axons reaching the fingertip is reduced by attrition at the suture line, axonal misdirection down the wrong endoneurial sheath, ar.d terminal connection mismatches. It is given that some minimal peripheral innervation density is critical for tactile discrimination. If only a third of fibers are slowly-adapting, and only, say, half the total number of fibers regenerate to the periphery, the critical innervation density for slow-adapters is more likely not to be met than for the quick-adapters. Furthermore, the degenerating Meissner corpuscle can be reinnervated by any one of the three to nine quickly-adapting axons that normally innervate it, while two to four degenerating Merkel cells are less likely to be reinnervated by the one slowly-adapting fiber that normally innervates them. Compounding this is the experimental observation that the Merkel cell degenerates more rapidly than Meissner corpuscle (Chapter 4). In essence, it is statistically highly more probable to reinnervate the Meissner corpuscles, the fiber/receptor system primarily tested by the moving two-point discrimination test.

There are two experimental studies that, in retrospect, support this hypothesis. Following nerve repair, there was a reduction in the number of slowly-adapting neuronal responses from 56 to 29% in Brodmann's area 3 while there was essentially no loss in the percentage of quickly-adapting neuronal responses in Brodmann's area 1 (see Fig.12.18).[40] Following nerve repair, an average of only 60% of the slowly-adapting fibers regenerated, and each fiber reinnervated only half of the Merkel cells it previously reinnervated.[41]

Finally, a comment about what fiber population is actually stimulated when the paper clip is moved along the surface of the fingertip. As the paper clip moves across the papillary ridges, it sets up not only a sequence of brief touches, but also a vibration within the area of its movement, similar to the disturbance the passenger in a car feels crossing railroad tracks. These low-frequency pertubations of the resting state in the fingertip pulp stimulate the entire Meissner afferent group of quickly-adapting fibers. Almost certainly, however, the remaining quickly-adapting fibers (the Pacinian afferents) will be stimulated as will the slowly-adapting fiber/ receptor systems. But as the paper clip moves along the fingertip due to the phenomenon of "recruitment," increasing responses will come from the quickly-adapting fiber/receptors. The slowly-adapting fiber/receptors, always in the minority, probably make only a functionally insignificant contribution to our perception of the two moving points. Therefore, I believe it is effectively correct to speak of this test as one that evaluates the innervation density of the quickly-adapting fiber/receptor system in general, and the Meissner afferents in particular.

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Chapter 9

VIBRATORY SENSE AND THE TUNING FORK

INTRODUCTION

"Pallesthesia," the sense of vibration what is it? Is there a distinct vibratory "sense" as there is a sense of smell: is the perception of a vibratory stimulus mediated by its own submodality specific neuroanatomic pathway, such as the perception of sound or light? The answer to these questions is "No."

From the time the doctor or therapist begins health care studies, he (she) is taught from the anatomist's archives and by the neurologist's classic approach. The perception of vibration, or vibratory sense, is taught as if it were a separate sensory submodality, such as pain, temperature, and touch. This is further confounded by being termed "bond conduction." Tuning forks are applied to bone prominences like the lateral malleoli, the frontal bone and the mastoid process. The final step in this subliminal indoctrination is the constant association of this "vibratory sense" with known spinal cord anatomy; "vibratory sense" is destroyed with lesions to the posterior white columns, the fasciculus cunneatus and gracilis.[1-5]

Vibration, or the "sense" of flutter-vibration is simply another touch submodality. Perception of a vibratory stimulus is the same as perception of successive, brief touch stimuli. As the neurophysiologist now have demonstrated clearly, the nerve fibers that mediate the perception of vibratory stimuli are the large myelinated fibers, the group A, beta fibers, and they are characterized as belonging to the quickly-adapting fiber group.[6-8] Thus, vibratory stimuli are mediated by the same nerve fiber population that mediates the perception of moving-touch!

The perception of low frequency vibratory stimuli, about 30 cycles per second (30 cps) is mediated by a quickly-adapting fiber/receptor system, the Meissner corpuscle in glabrous skin, and the hair follicle lanceolate endings in the hairy skin (see Chapter 3).

The clinical evaluation of vibratory perception tests the same neural pathway as moving-touch. These do go from the fingertip to the brain via the posterior spinal white columns. Vibratory stimuli, however, offer unique possibilities in evaluating peripheral sensibility. Testing is readily done with the tuning for, an instrument almost as prevalent as the ubiquitous paper clip. Patients are generally naïve in tuning fork experiences. A tuning fork stimulus, therefore, is usually a new experience, and the patient need not involve his “association” cortex in an attempt to label or name his perception. He need only answer whether or not he perceives “something” and compare it to another fingertip’s perception of the same stimulus. Vibratory perception is nonnoxious: drunks are awakened by it, children laugh at it, the acutely injured patient is not further discomforted by it.

PREVIOUS CLINICAL STUDIES

Diabetes mellitus was among the first disease states to be studied with vibratory stimuli. Williamson[9] was the first to note diminished vibratory perception in diabetic neuropathy. Observations by others soon followed[10] and continued to be refined.[11] Clinical evaluation of other forms of peripheral neuritis included those associated with tabes and pernicious anemia.[12,13]

Investigation into vibratory perception in the normal population demonstrated decreasing perception with increasing age, with this loss being due primarily to changes in threshold.[11, 13-15]

Reports of vibratory stimuli used to evaluate peripheral sensibility in the hand are few (Table 9.1). Minor[16] may have been the first to note abnormal vibratory perception following nerve injury (1904). In 1936, Gilmer[17] briefly reported a patient with a palm laceration who had divided the common volar digital nerves to the middle, ring, and little fingers. The injury was followed for 2 years. A nerve repair is not stated explicitly. The earliest perception to return was low-frequency vibratory perception with high amplitude at the fingertip. At 2 years, thresholds were returning to normal and higher frequencies could be perceived.[17]

In 1970, McQuillan[18] tested a “mechanical vibrotactile stimulator” in which he varied stimulus amplitude and frequency to get a “sensogram” similar to an audiogram. His subsequent report[19] compared these sensogram with classic two-point discrimination in 13 uninjured “controls” and in seven patients following median nerve repair. He concluded that “sensibility to vibratory stimuli is lost after median nerve division. The loss diminishes with the passage of time after nerve repair. The degree of loss of vibratory sensibility can be accurately measured,” and that vibrotactile threshold assessment is superior to two-point discrimination as a method of assessment of results of nerve repair” However, the “sensogram” calculations require the determination of the difference between vibratory thresholds for successive tuning curves during the course of sensory recovery. Though perhaps highly accurate, I feel this method is cumbersome and not readily applicable.

In 1972, I reported the use of two tuning forks, 30 and 256 cps in evaluating recovery of sensation following nerve repair.[20] These frequencies related to the maximum sensitivities of the two subpopulations of quickly-adapting fibers as determined by Mountcastle,[8] and were believed to be related to the Meissner and Pacinian end organs, respectively. Tuning forks were subsequently reported useful in determining when to initiate sensory re-education[21] (see Chapter 12). Evaluating sensory recovery with tuning fork has since been used by Jabaley et al,[22] in attempting to correlate the clinical results of nerve repair with the histologic pattern of reinnervation and by Lindblom and Meyerson[23] in evaluating the functional results of digital replantation.

Table 9.1
Diagnosis of Bilateral, Carpal and Cubital Tunnel Syndromes[a]

Vibratory Stimuli	Right		Left	
	Thumb	Little Finger	Thumb	Little Finger
256 cps	±	±	±	±
30 cps	±	±	±	±
t_{120}	.36	.50	.36	.50
Two-point				
Classic	6	8	6	8
Moving	4	4	4	4
Hand-dorsum				
Ulnar vs radial	↓		↓	

Table 9.1 Diagnosis of Bilateral, Carpal and Cubital Tunnel Syndromes[a] [[a]These carpal and cubital tunnel syndromes were in a 20-year-old woman with rheumatoid arthritis.]

Most recently, I reported our clinical experience with the use of vibratory stimuli to evaluate peripheral nerve injury and compression neuropathy.[24] The study evaluated 148 injured nerves in 101 patient, and demonstrated that the tuning fork is an acceptable convenient, simple and quick test of nerve integrity in the emergency milieu. The study further demonstrated that altered vibratory perception is possibly the earliest clinical finding in peripheral compression neuropathy, and may, therefore, be the best sensory test with which to monitor compartment syndrome. The results of the study will be discussed in detail below.

TUNING FORK

The earliest observations on vibratory perception are those of Valentin from 1852. He was studying the “sense of touch impression.” He modeled his test instrument after clockworks or small thin wheels with teeth. He called his instrument a “Tastscheibe,” a touch disc or cogwheel. By knowing the number of teeth on the wheel and how fast he was moving it across the fingertip, he could calculate touch frequencies. In an analogy to the flicker-fusion phenomenon in optics, he was interested in when the perception of many small touches became altered, and in the capacity of nerves to transmit these rapid frequency stimuli.[25]

Von Wittich's work, reported in 1869, is cited by both von Frey[26] and in the review by Fox and Klemperer[27] as using this cogwheel to study vibration. von Wittich also reportedly[26] employed organ pipes for his vibratory studies.

Rumpf[28] introduced the tuning fork into clinical use in 1889. He employed a set of 14 tuning forks with frequencies ranging from 13 to 1000 cps. He reported normal values and observations on a case of syringomyelia. In 1899, Gradenigo[29] modified the tuning forks for auditory testing. By adding a calibrated black and white triangle to the vibrating prongs, he could calibrate amplitude and thus stimulus intensity. Symms[30] introduced the tuning fork into neurology in 1918.

Of interest is von Frey's comment[26] that prior investigations (before 1915) used the tuning fork by striking its prongs and placing the single stem end against the test area. He believed that vibratory perception was mediated through receptors in the skin. He believed that vibration was repetitive touch stimuli and not a separate vibratory sense. To test vibration, he attached a "sensory hair" to the prong of a 100-cps, electromagnetically driven, tuning fork. I believe, therefore, that von Frey was the first to use the pronged end of the tuning fork as the stimulus end.

To appreciate von Frey's contribution in this area it must be recalled that "bone conduction" a term still with us originated with Max Egger in 1899.[31] Egger believed that the receptor for vibratory perception was bone and that the tuning fork was the best instrument to test skeletal sensibility." This theory was challenged by Rydel and Seiffer in 1903. Their clinical observations led them to conclude vibration was perceived not only of bone, but also by the fine nerve fibers beneath the skin.[31] Minor also argued against bone being the receptor of the vibratory "sense."[16] During his investigations, von Frey actually anesthetized the skin with a novocaine solution containing adrenalin ("suprarenin"). He found vibratory perception diminished only in the "white" skin areas. He believed cutaneous receptors perceived vibration and that bone was a simple mechanical conductor of the vibratory wave to other area of skin.[26]

Today, the tuning fork has left the realm of curiosity. Indeed, it has become almost commonplace, and perhaps as such, almost ignored. Although virtually every second year medical student arms himself with a tuning fork before entering the clinical arena, the progressively parochial training course towards medical specialist reduces the ranks of those armed with tuning forks to those in the neurosciences. Nevertheless, tuning forks are standard hospital equipment and are found routinely in the drawer in the examining room, in the physical exam box in the nurses' station, and in the emergency room (Fig. 9.1). The available tuning fork is usually one capable of vibrating in the midfrequency range, 128 or 256 cps.

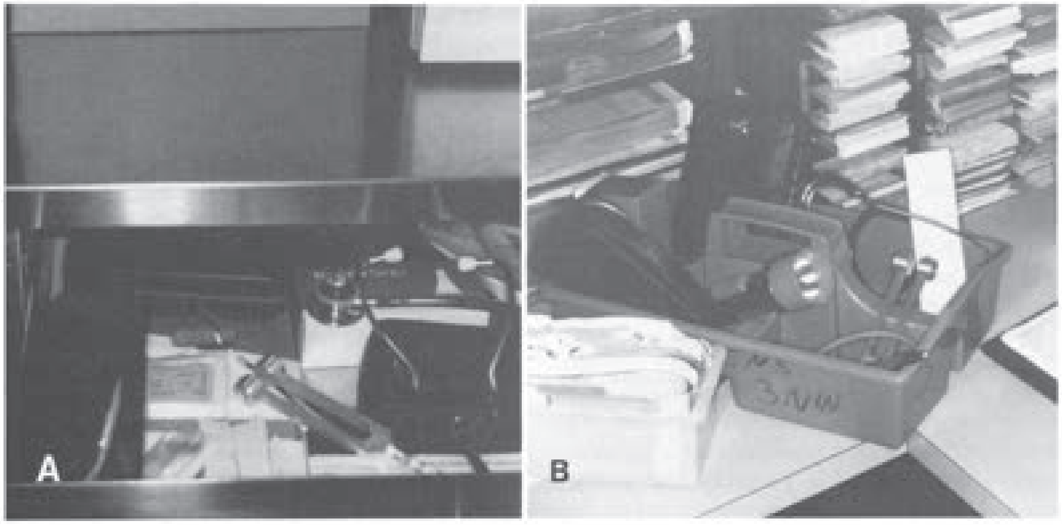


Figure 9.1. Tuning forks are standard hospital equipment. They can be found in the drawer of the consultation room (*A*) and in the physical exam tray or basket in the ward (*B*).

The technique of tuning fork application that is taught traditionally in medical school contrasts to the technique I suggest for evaluating sensibility in the hand (Fig 9.2). Traditionally, the base or the nonpronged end of the tuning fork is applied to a thin-skinned bony prominence:

> The examination was conducted in the following manner: the same force of blow being used each time, the fork was struck and the base in contact with the styloid process of the ulna. The patient was asked to describe what he felt. If his description did not indicate a distinct perception of the vibration, he was tested with the nonvibrating fork and asked if there was any difference between the two contacts. If he did not perceive any, he was not examined further. If he gave a clear description, the fork was struck again, and he was asked to state the instant the sensation ceased. Then the prongs were touched to stop the vibration, and if he did not reply instantly, the examination was discontinued. If his reply was simultaneous with the cessation of vibration, the fork was struck again and the length of time the vibration was felt was estimated with a stopwatch. Five such examinations were made on each of the following bony point: styloid process of the ulna, styloid process of the radius, olecranon process, internal malleolus, external malleolus, tibia and patella. If there was a considerable discrepancy in the results obtained from any one point, ten trials were made at that point the results presented are the averages of at least five trials for each point tested. In order that the element of fatigue might be excluded as much as possible, two successive examination were not made at one place.[27]

I believe that when the tuning fork is employed to evaluate peripheral sensibility in contrast to cranial nerve VIII or the posterior spinal tracts, the prolonged ends of the tuning fork should be employed. The fingertips have significant subcutaneous tissue interposed between the skin and bone, and the prongs, having greater amplitude of vibration than the base of the tuning fork, provide a more intense stimulus. The normal threshold for vibration varies with the stimulus frequency. The lower frequencies have a high threshold, and therefore require a greater amplitude for perception.[8] In the normal hand the threshold values are all low, and the vibrating tuning fork base certainly can be perceived. However, in nerve compression and following nerve repair, the thresholds are significantly increased. Accordingly, I feel that the greater amplitude available at the pronged end makes the pronged end the stimulus of choice in evaluating peripheral sensibility. The examiner will be using a supramaximal stimulus. The patient's altered perception therefore, cannot be due to using a stimulus of insufficient intensity (Fig. 9.2).

Which frequency tuning fork should be chosen? As discussed in Chapter 3, the 30-cps tuning fork is best to evaluate the Meissner afferents, the quickly-adapting fiber/receptor system located in the superficial dermis. The 256-cps tuning fork is best to evaluate the Pacinian afferents, the quickly-adapting fiber/receptor system located in the deep dermis and subcutis. Both are needed if you are (1) following the recovery of sensation after nerve injury; (2) deciding the appropriate timing and phase of sensory re-education; and (3) investigating peripheral sensibility. However, for clinical evaluation of nerve injury, either nerve compression or nerve division, both appear to be equally valid and, as a matter of convenience, I use the small 256-cps tuning fork. Any available tuning fork may be used in the range between 30 and 256-cps. I have no experience with the 5112-cps tuning fork, but feel that it may not stimulate enough of the low-frequency responsive Meissner afferent to reflect accurately the status of the entire quickly-adapting fiber population.

How do you evaluate the patient's perception of the tuning fork stimulus? This can only be done qualitatively. Precisely for this reason, that is, in order to have a quantitative evaluation of vibratory sensibility, the "pallesthesiometers" were developed (see next section). For most clinical evaluations, however, a qualitative assessment is both accurate and sufficient.

TESTING

In order to achieve a vibratory stimulus of sufficient intensity (amplitude) to evaluate the compressible, spongy fingertip pad, we hold the tuning fork's prong tangentially to the fingertip. The area to be tested is always compared to its contralateral area. Additionally, the area is compared to an ipsilateral noninvolved area. For example, if the patient, by history, has a right carpal tunnel syndrome, the right thumb and index finger are tested and compared to the right little finger (ulnar versus median innervated) and to the left thumb and index finger. If the patient reports altered perception of either of the vibratory stimuli in either thumb or index finger in the test areas in contrast to any control areas, the evaluation is recorded as "abnormal." For example if the patient by inspection, has a laceration over the radial side of the right index finger's proximal phalanx, the radial side of the right index finger just distal to the interphalangeal joint (but not the fingertip) is tested and compared to the finger's ulnar digital nerve "autonomous zone" and to the radial side of the left index finger. Again, if the patient reports altered perception of either of the vibratory stimuli in comparison to either the ipsilateral ulnar digital or contralateral radial digital area, the evaluation is recorded as abnormal. The tuning fork is struck anew between each test area. The examiner uses his own acoustic perception of the resultant vibration, as well as his own tactile feedback of the striking force (and the pain generated in his patella) to judge roughly equivalent supramaximal stimulus intensities.

If an altered perception is elicited, the stimulus is repeated again. Perception is judged "altered" if the patient answers affirmatively to the question, "Did those two feel *different?"* This is followed by the question "How did they feel?" Response examples judged "positive" for an abnormal perception are: "I didn't feel anything," "It felt softer, or louder, or quieter", or "as if my finger were covered with a layer of cloth," etc. not asked is the question: "Did you feel *that?"* The patient, whose eyes are shut when the fingertip is stimulated, is also asked to localize the perception. Often with a digital nerve divided at the middle phalanx or a median nerve division, a vibration is perceived when the fingertip is stimulated but the perception is localized to the finger's dorsum. This occurs not because the nerve being tested is functioning, but because the vibratory wave travels down the finger, stimulating a nerve innervating an adjacent nerve territory.

VIBROMETER

The need of basic scientists and clinical investigators to quantitate the vibratory threshold led to the production of various "pallesthesiometers." Many of the early investigators believed that vibration was not touch, but a separate sense. In 1890, Thompson[33], described the "extraordinary" ability of two dear people to know of changes in their immediate environment by perceiving transmitted vibrations. He wrote vibration "… almost assumes the dignity of a special sense." Treitel[34] was a strong advocate of vibration being a separate sense. He observed in 1897 that 128-cps stimulus was not well perceived in the lips and cheek, places which were very sensitive to touch. Furthermore, in cases of syphilitic and alcoholic neuritis, vibration could be perceived while perception of touch was lost. Thus, Rydel[40] felt it appropriate to name this special sense of whirring from the Greek word for quivering: the term "Pallesthesia" was born. The instrument to measure this "sense" would be termed, of course a "pallesthesiometer." Because , as discussed in this chapters introduction "vibratory sense" is not a separate sense, the term "vibrometer" will be used throughout the remainder of this section. (A good historical review of this "separate sense" question is available by Geldard[35].

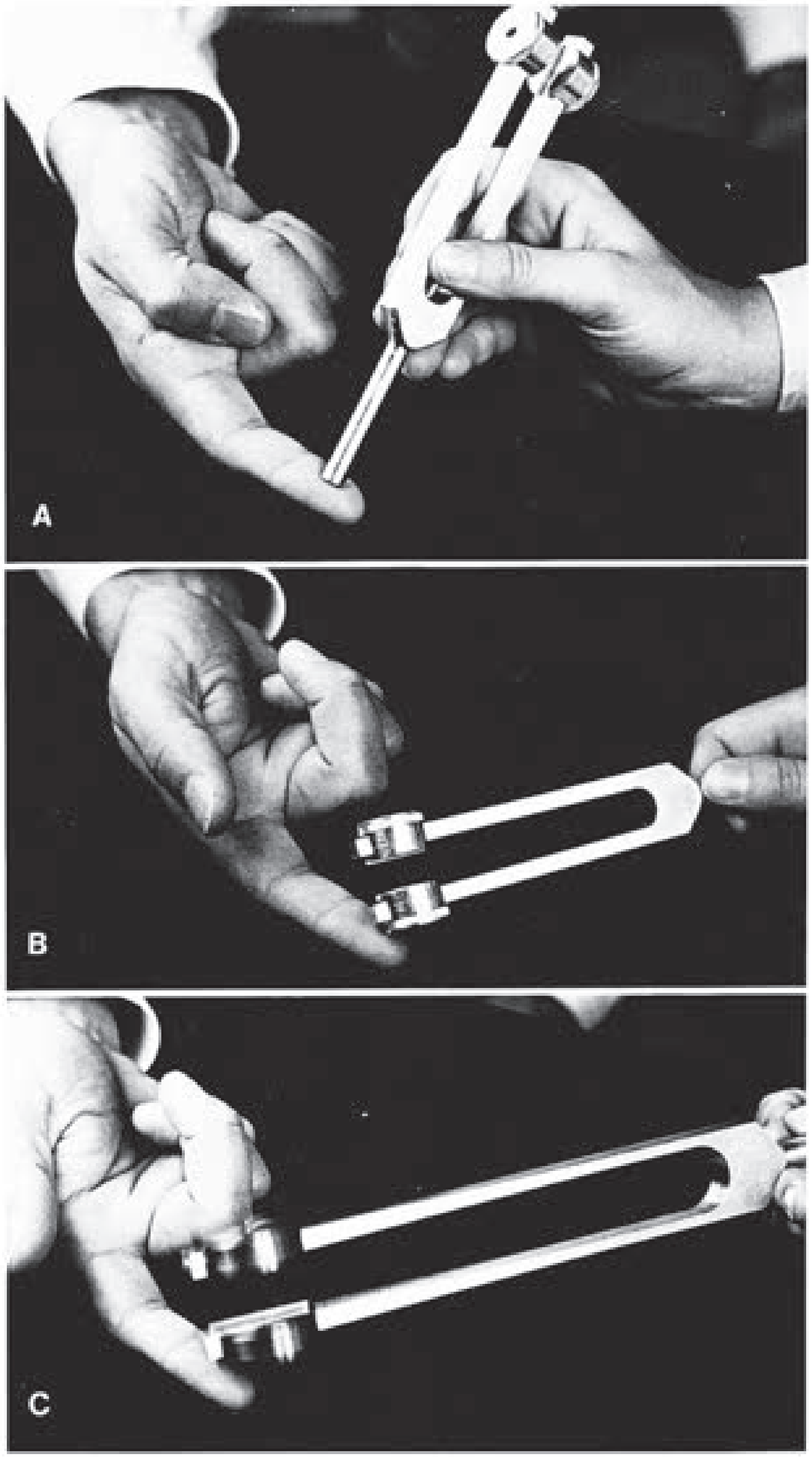


Figure 9.2. Method of tuning fork use. *A*, Traditional techniques as applied by neurologists and otorhinolaryngologists to bony prominences. *B* and *C*, Technique suggested for evaluating peripheral sensibility. The prong end has greater amplitude and is more suitable to test the fingertip pulp in patients with altered vibratory threshold.

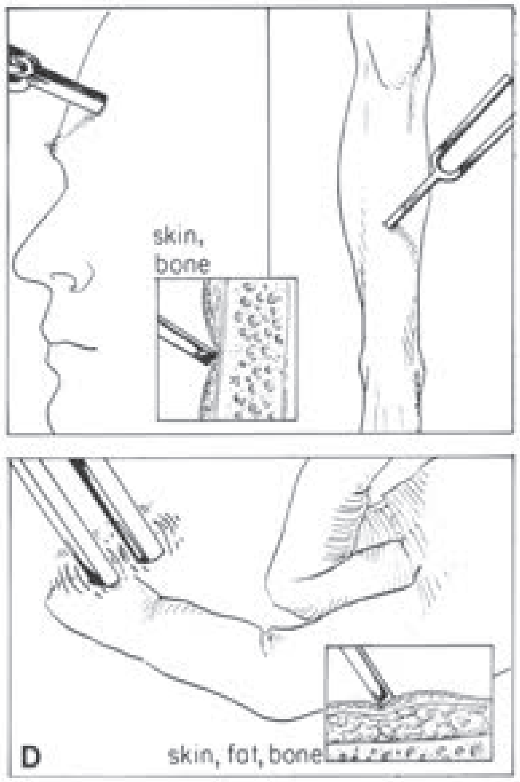


Figure 9.2. ***D***, Traditional areas of fork application are in close proximity to bone. The fingertip has greater volume of subcutaneous tissue.

The most quantitative a tuning fork assessment could be was to count the seconds from the stimulus perception to stimulus fade out, as recommended by Williamson,[9] or the so-called "alternate displacement method," recommended by Head.[36] In this latter method, the lapsed time is measured between the cessation of vibratory perception on one side and the moment when the fork, still vibrating, is no longer perceived on the contralateral side.

To quantitate vibratory threshold, the vibratory stimulus had to be controlled. An electrically controlled "rheocord" was described in 1902,[37] and an electromagnetically driven fork in 1904.[16]

Two basic vibrometer variations were developed ultimately: frequency could be varied with amplitude constant, such as the model that was utilized to test Helen Keller,[36] or amplitude could be varied, with a constant frequency, usually chosen as 120cps, because of the 60-cycle alternating current circuit.[39, 40] Cosh [13] has described a vibrometer in which both frequency and amplitudes can be varied. Recently (1977) Daniel et al.[41] with a uremic population reported on the value of the "Biothesiometer", a variation on the amplitude-variable model. Our experience with this model has been reported, and will be summarized below (Fig. 9.3).[42]

I believe the vibratory threshold stands I relation to the moving two-point discrimination test as the von Frey hair measurement does to the classic two-point discrimination test. The vibratory threshold, determined at a given frequency and at a given "spot" on the fingertip tells you the functional status of a given quickly-adapting fiber/receptor, or its peripheral receptive field. If the threshold is low (normal), a single fiber and its peripheral receptive field are either (1) normal or (2) recovered from the injury, compression or repair. However, a single functioning nerve fiber and its peripheral field are insufficient for tactile gnosis. Tactile gnosis requires a "large number" of overlapping peripheral receptive fields. Evaluation of this capacity requires a measurement of the innervation density of this system: which is provided by the moving two-point discrimination test. Thus, a patient may perceive a 30-cps and 256-cps at his fingertip, but still be unable to identify an object placed within his fingertips (see Chapter 10 for these functional correlations of sensory testing).

Vibratory threshold determinations are useful occasionally in diagnostic dilemmas. The patient with bilateral nerve compressions deprives the clinician of his normal "contralateral control." In these instances, having available an "absolute" such as the vibratory threshold can be helpful. For example, with a bilateral carpal tunnel syndrome, the tuning fork test demonstrates usually an equal perception of the stimulus between both thumbs. The perception is nearly always considered much better or "louder in the little fingers." However, the situation may arise with bilateral carpal and bilateral cubital tunnel syndromes (I've seen this three times) where vibratory thresholds can demonstrate that although vibratory perception is uniform in all fingers, it is really uniformly reduced. However, in my experience, by the time this has occurred, the moving two-point discrimination test is also abnormal (Table 9.1)[42] Of course, electrodiagnostic studies are also available (though not "on the spot" and they are "invasive" and expensive).

The vibratory threshold is abnormal in peripheral nerve compression syndromes such as carpal tunnel and cubital tunnel syndromes. With surgical decompression of the involved nerve, the abnormal high thresholds return to normal.[42] Although vibratory threshold determinations are not required for diagnosis in the routine situation, the observed improvement in threshold value can be useful in monitoring the patient postoperatively. In the patient following ulnar nerve release at the elbow, where there is loss of tactile discrimination preoperatively, often the postoperative hyperesthesia or slow course of recovery are taken by the patient as sign that the operation was not "successful." In such circumstances, demonstration that the vibratory threshold has improved provides the "objective proof needed for patient (as well as physician) reassurance. The not infrequent combination of median-at-the-wrist and ulnar-at-the-elbow compression offers another situation for reassurance. Relief of the carpal tunnel symptoms is often quick and dramatic, while the little finger paresthesia persists. In complex hand injuries, neurolysis follow-up is also aided by threshold monitoring (Table 9.2)

In summary, I have found[41] vibratory threshold measurements are accurate, easy to do, and quick. They give values whose interpretation, allowing for age-variance, is in agreement with our standard sensory evaluation techniques (the paper clip and tuning fork). Vibratory threshold measurements rarely have been required for diagnosis. Vibratory threshold measurements have been of value in the office setting, primarily in longitudinal studies, where progressive improvement in the threshold has proven reassuring at a time prior to recovery of moving two-point discrimination.

POSITION SENSE

In many ways, the "position sense" is similar to the "vibratory sense." We again have been conditioned early in our training to believe that there is a "sense" that deals with keeping us informed of the location, in three-dimensional space, of one part of our body with respect to another. Again, like vibration, we are told that this "sense" I conveyed by fibers traveling in the posterior spinal tracts, whose impulses are generated by joint receptors and musculotendenous junctures

Erik Moberg[43, 44] deserves the credit for bringing to our attention the very important observation that "position sense" or proprioception is primarily related to cutaneous sensibility the realization came during his work with tetraplegics. I thank him for reminding me of the work from the Department of Orthopedics at Johns Hopkins in which patients who had total hip replacements were still able to demonstrate good hip position sense.[45] Previously, Gelfan and Carrier[46] had demonstrated that there is no "muscle sense" in man. A pull on tendons at the wrist did not cause awake volunteers to perceive finger movement. Only finger movement did this.

Certainly there are quickly-(Pacinian) and slowly-(Rufini) adapting endings within joint capsules, but they appear to initiate impulses at the extremes of their joint's range of motion,, acting more in a protective way than for true proprioception.[47, 48]

There is a close relationship between "vibratory sense" and "position sense," both of which are conveyed via the group A beta fiber population. In 1936, Newman and Corbin,[49] in a paper primarily concerned with describing a variable-amplitude, 60-cps vibrometer, noted that vibratory threshold increased with age and was increased in "arthritics." They went on to conclude: "This would seem to imply that arthritic patients have a greater loss of proprioceptive fibers than a similar age group of normal." In 1942 Fox and Klemperer[27] evaluated vibratory threshold in the hands of patients with brain lesions.[27] Although they did not comment directly on their observations,, the three hand diagram in which impaired position sense was designated for each finger, clearly show a direct correlation between elevated vibratory threshold and impaired position sense. In each of these patients, stereognosis was also severely impaired.

Moberg has found an excellent correlation between two-point discrimination and proprioception in the hand, that is, the best predictor of who will be able to identify correctly the position change of his finger is the two-point discrimination test.[43]

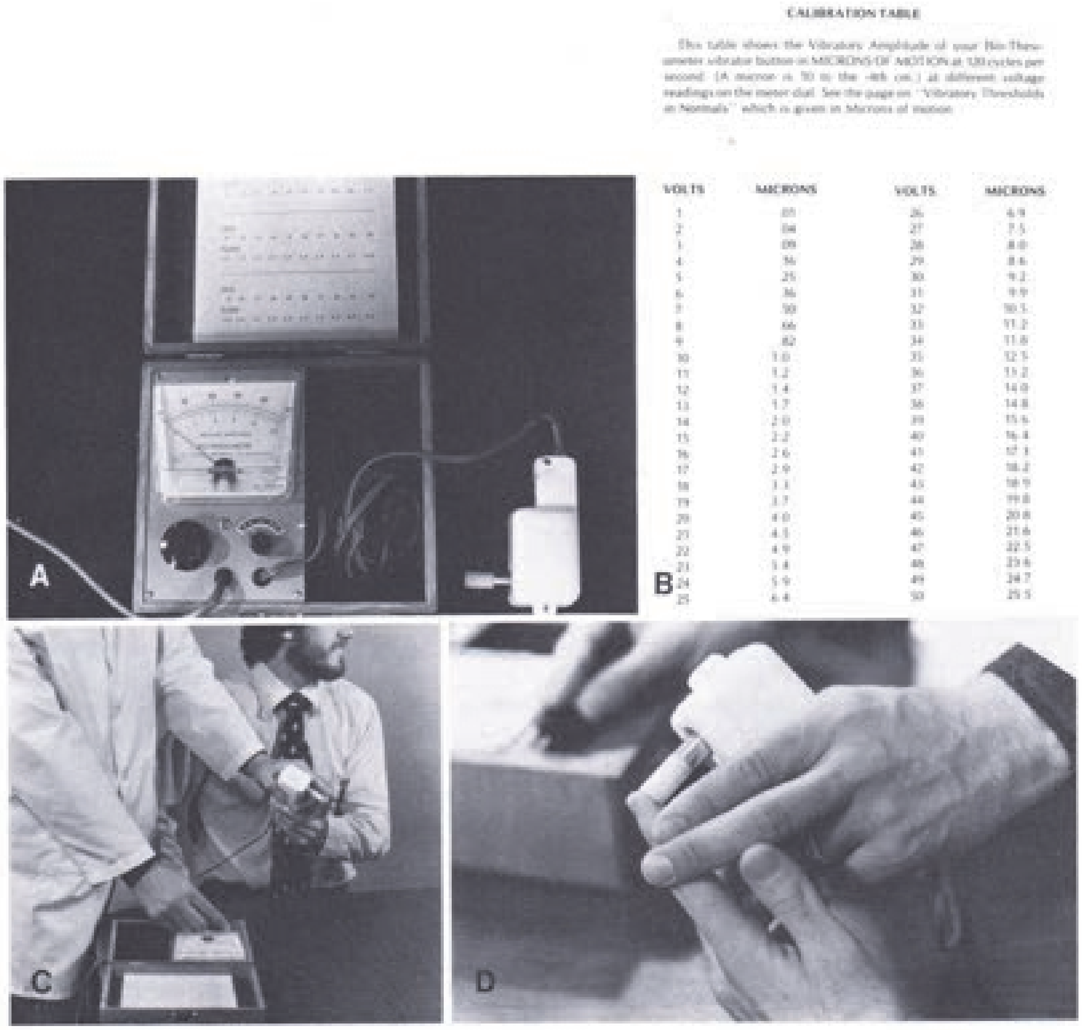


Figure 9.3. The vibrometer. Illustrated (*A*) is the Biothesiometer, an amplitude-variable, fixed frequency (120 cps) instrument. *C* and *D*, End of vibrator is held in contact with the fingertip while the stimulus intensity is gradually increased. The threshold is as the voltage required to deliver the perceived stimulus. Voltage is converted to microns of displacement (stimulus intensity) from the calibration chart (*B*).

Table 9.2
Neurolysis Ulnar Nerve in Wrist and Palm Six Months Following Electrical Burn and Skin Grafting[a]

Date	Thumb				Little Finger			
	m2PD (mm)	2PD (mm)	256	t_{120}	m2PD (mm)	2PD (mm)	256	t_{120}
Preoperation								
11/13/79	2	3	nl	.16	6	18	↓↓	1.0
Operation								
1/10/80								
Postoperation								
2/22/80	2	3	nl	.16	4	10		.36
3/14/80	2	3	nl	.16	3	5	nl	.25
5/30/80	2	3	nl	.16	2	4	nl	.16

Table 9.2 Neurolysis Ulnar Nerve in Wrist and Palm Six Months Following Electrical Burn and Skin Grafting(a)

Most recently, Clark et al.[50] have published a study involving percutaneous single-unit nerve recording in awake human subjects. One group of volunteers had intraarticular (knee) local anesthesia and another had a local block of the skin in a 15-cm band about the knee. With either or both types of block, subjects could still correctly identify lower leg position. Does this mean that cutaneous sensibility is not needed for proprioception? No! The band of skin anesthetized was too narrow. Skin of the entire thigh and lower leg has traction exerted upon it with knee flexion/extension.

Another recent study, utilizing percutaneous single-unit nerve recordings, defined the extent of activation of the different mechanoreceptive afferents during finger movement.[51] In brief, all four categories (Meissner and Pacinian groups of quickly-adapting, and types I and II slowly-adapting) were excited by voluntary finger movements. Slowly-adapting units were active during static finger positions. Few true joint receptors (fibers where activity was present only with joint movement and for which there were no peripheral receptive cutaneous field) could be found thus, the mechanism of cutaneous sensibility has the capacity to mediate position sense.

In summary, I believe that position sense is a complex function comprised of afferent impulses from three sources (1) the musculotendinous afferent which may affect primary synergistic/antagonistic muscle balances and impact minimally at the conscious level; (2) the joint receptors, which appear to begin entering the conscious level only as potentially injurious joint activity (extremes) is approached; and (3) the large, myelinated nerves subserving cutaneous sensibility (probably the slowly-adapting fiber/receptor system) which appears to be primarily responsible for the awareness of joint position in the functional range.

CLINICAL APPLICATIONS

Nerve Division

Most clinicians feel they can diagnose an acute nerve injury, certainly a completely divided nerve in the upper extremity and the vast majority of clinicians could easily, make the diagnosis of a divided median or ulnar nerve at the wrist. But how about a partial nerve injury? How about the same evaluation in a child? And what of the more distal hand injuries, say in the palm, through a small wound not associated with tendon injuries? The isolated digital nerve injury, without associated tendon injury is perhaps the most difficult to diagnose, even for experienced examiners.

I feel the tuning fork offers several advantages in the diagnosis of nerve locations. The vibratory stimulus is gentle, nonthreatening, noninvasive, and accurate. Children accept it. Drunks accept it. The patient in pain accepts it. The tuning fork can be applied to a bandaged hand without having to unwrap it. It is quick. These advantages were demonstrated[42] in patients with upper extremity lacerations potentially involving nerve.

In 48 patients with 78 nerves at risk for potential division evaluation of sensibility with vibratory stimuli was correlated with anatomic findings with surgical exploration this included six median, five ulnar, two radial, and 65 digital nerves. Altered vibratory perception correlated in all cases with conduction block in the nerve. There were 0% false positives (Fig 9.3). We use the term “conduction block” because in four of the 52 nerves evaluated for which diminished vibration was perceived, the nerves (digital) were still intact: in two they were stretched and lax, having sustained a “stretchy palsy” (snow blower injury) and in two there were contused and hemorrhagic (having had epineurium stripped) (Fig. 9.4). The other 26 nerves although lying directly below a deep skin laceration, were judged to be intact on the basis of the patients perception of the vibration (Fig. 9.5). In each of these cases at surgical exploration the nerves were intact. There were 0% false negatives (Table 9.3)

Evaluation of the puncture wound to the palm with associated sensory change is a challenge. The offending agent is commonly a knife or a piece of glass. Conceivably, the numbness or paresthesia over the web space (most usually the ring/little finger web) could be from a contusion to the nerve. Often the patient is not agreeable to exploration of “such a small hole.” In these instances, the tuning fork examination usually demonstrates diminished vibratory perception over the distribution of the digital nerve or common volar digital nerve in question. I advise waiting 4 to 6 weeks and begin tetanus/antibiotic prophylaxis. I follow them at regular, close intervals. In only one of our patients has vibratory perception returned to normal, accompanied by a progressive decrease in palmar pain over 4 weeks, with ultimate complete recovery. Five other patients had persistent decrease in vibratory perception and palmar pain. These patients were explored. Three had complete divisions, requiring secondary repair or grafting. Two had incontinuity neuromas, requiring secondary repair (Fig. 9.6). I repaired the nerve as much to relieve the palmar pain as to restore peripheral sensibility.

Figure 9.4. Evaluation of potential acute nerve injury. *A*, Patient had lacerations to fingers sutures and was then referred for "tendon injury to middle finger." Preoperative tuning fork evaluation was abnormal. *B*, Intraoperative evaluation demonstrated complete division of ulnar neurovascular bundle and radial digital nerve in addition to tendon injury.

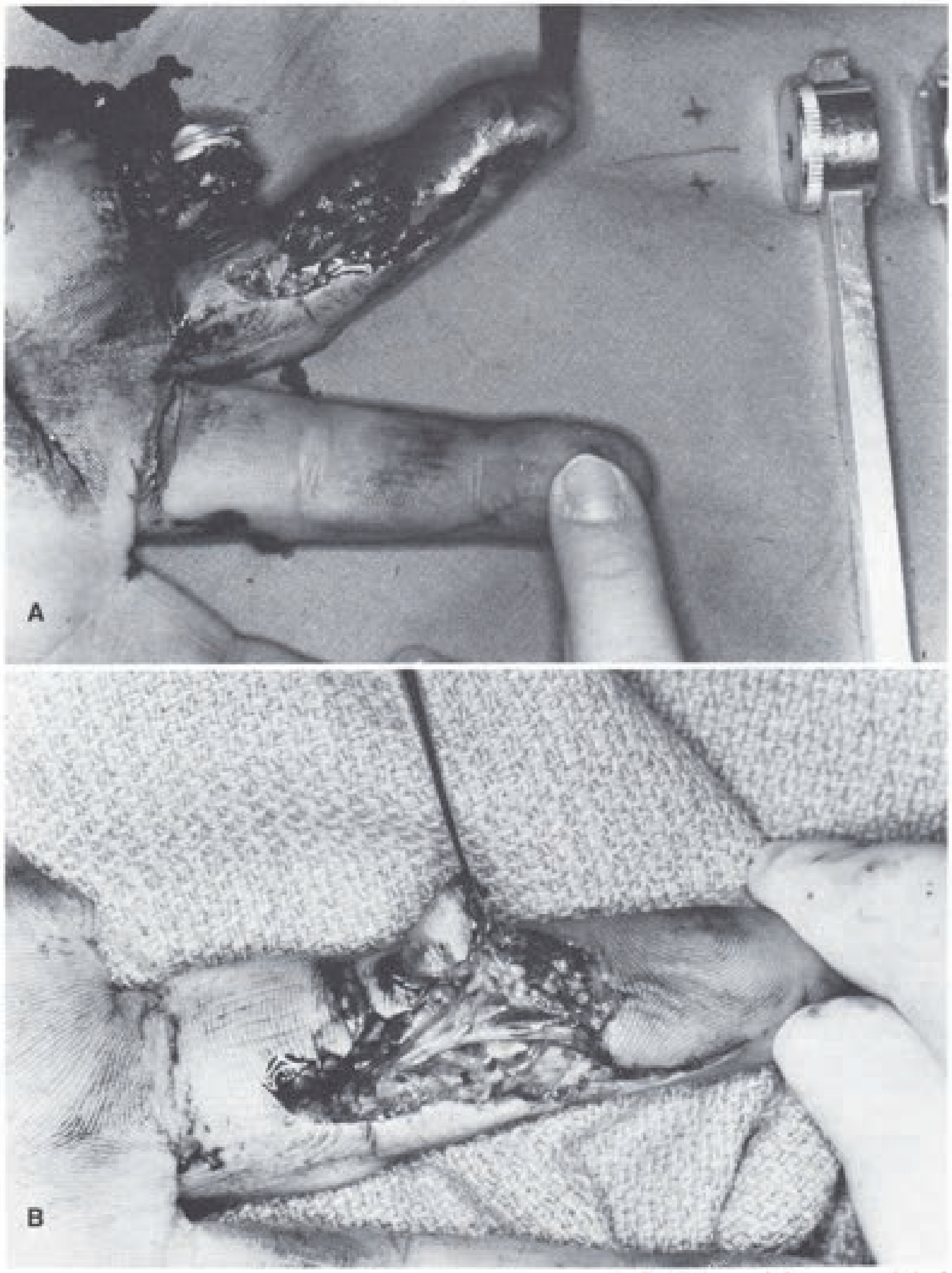


Figure 9.5. Evaluation of potential acute nerve injury. *A*, Radical saw injury amputated little finger and avulsed segment of soft tissue from side of ring finger. Vibratory perception was normal. *B*, At exploration, digital nerve was found intact, without either contusion or stripped epineurium.

Table 9.3
Evaluation of Potential Acute Nerve Injuries*

Vibratory Perception	Clinical Evaluation	Operative Findings (%)	
Normal (n = 26)	Nerve functioning	Nerve intact	100
Abnormal (n = 52)	Nerve conduction blocked	Nerve divided	92
		Nerve stretched	4
		Nerve contused	4

* n = number in group.

Evaluation of the isolated digital nerve injury is so difficult because there is overlap at the fingertip. The autonomous zone is proximal to the fingertip and doesn't extend to the volar midline (Fig. 9.7). Some authors[52, 53] have suggested this overlap in the pulp doesn't exist. Wallace and Coupland,[54] for example, carried out an anatomic dissection on 25 thumbs and 25 index fingers. They found that "no evidence of cross-over of nerve supply to the other side of the thumb… (or) of the pulp was apparent." However these were the gross dissections done on embalmed specimens. The appropriate study would involve nerve-staining a serially sectioned finger pulp from a patient with a single digital nerve injury. If such a possibility were encountered, that histologic investigation would be important. There is no doubt, clinically that such pulp overlaps occur; often patients have been referred to me who "could feel the needle stick in the fingertip" when examined in the emergency room, who later required repair of their digital nerve injury (Fig. 9.8). Weckesser[54] tested two-point discrimination before and after a digital nerve block in patients after digital nerve repair. In the majority of patients, the value changed after nerve block, demonstrating function overlap (Fig. 9.9). Poppen et al.[55] have again emphasized the problem of diagnosing and evaluating recovery in a single digital nerve injury precisely because of this overlap at the pulp. A recent (1975) description of how to diagnose a digital nerve injury demonstrates the inadequacy of most current approaches to this problem.[56]

> The examination may be confined to testing the reaction to pain either by pain-pinch or by pinching the skin of the finger and fingertip with forceps. Sometimes nerve damage can be diagnosed by inspection of the wound. During the convalescent period, a more detailed examination is necessary including two-point discrimination of tactile gnosis, but these tests are often difficult to do successfully on digital nerve lesions.[56]

I studied 20 fingers which had a single completely divided, digital nerve, and evaluated them for the perception of constant-touch moving touch, 30- and 256-cps stimuli, and classic and moving two-point discrimination. In every case, the patient stated he could feel the examiner's fingers moving over the so-called autonomous zone of the divided nerve. Testing done to the finger's tip was usually normal. In every case, the patient stated he could feel something touch him when the examiner's finger pressed, with any but the lightest touch, upon this same area. Classic two-point discrimination was greater than or equal to 8 mm (transversely across the finger), and moving two-point discrimination was greater than or equal to 6 mmm in comparison to the 2 to 3 mm discrimination on the noninjured side of the finger. If the digital nerve was divided proximal to the branch to the dorsum of the finger, then the two-point discrimination were each greater than or equal to 10 mm. Perception of either 30-cps or 256-cps stimuli was always perceived as diminished over the test area when compared to the noninjured side.

In summary, I feel that tuning fork testing, in which a perceived difference in vibration exists between the two tested autonomous zones of the digit, is a highly accurate diagnostic test for digital nerve injury. In acute injuries, I feel it is the method of choice.

NERVE COMPRESSION

Mechanisms / Diagnosis

Basic to the diagnosis of nerve compression is the pathophysiology. Understanding the mechanism of compression neuropathy gives insight into the best diagnostic approach. For example after 25 years' experience with 1,201 cases of chronic nerve compression (carpal tunnel syndrome) Posch and Marcotte,[57] make the diagnosis as follows:

> On examination, dryness over the thumb and first 2.5 fingers leads one readily to a diagnosis of carpal tunnel syndrome. Examination with pin prick for decreased sensation is extremely important. Thenar atrophy is noted in long-standing cases.

Dryness, due to loss of function of the sympathetics, and analgesia, due to loss of function of the pain fibers, are related to the thinnest nerve fibers in the median nerve. Are the thinnest fibers the first fibers to lose function? Surely, muscle atrophy is diagnostic, but what should the earliest signs be? It was only a generation ago that before the surgeon (Learmonth) was called by the neurologist (Wolman) at the Mayo Clinic the diagnosis required "the tips of the second and third digits … with vesicles and ulcers … and complete anesthesia" to be present.[58] Present knowledge of pathogenesis and neurophysiology should allow a different approach today.

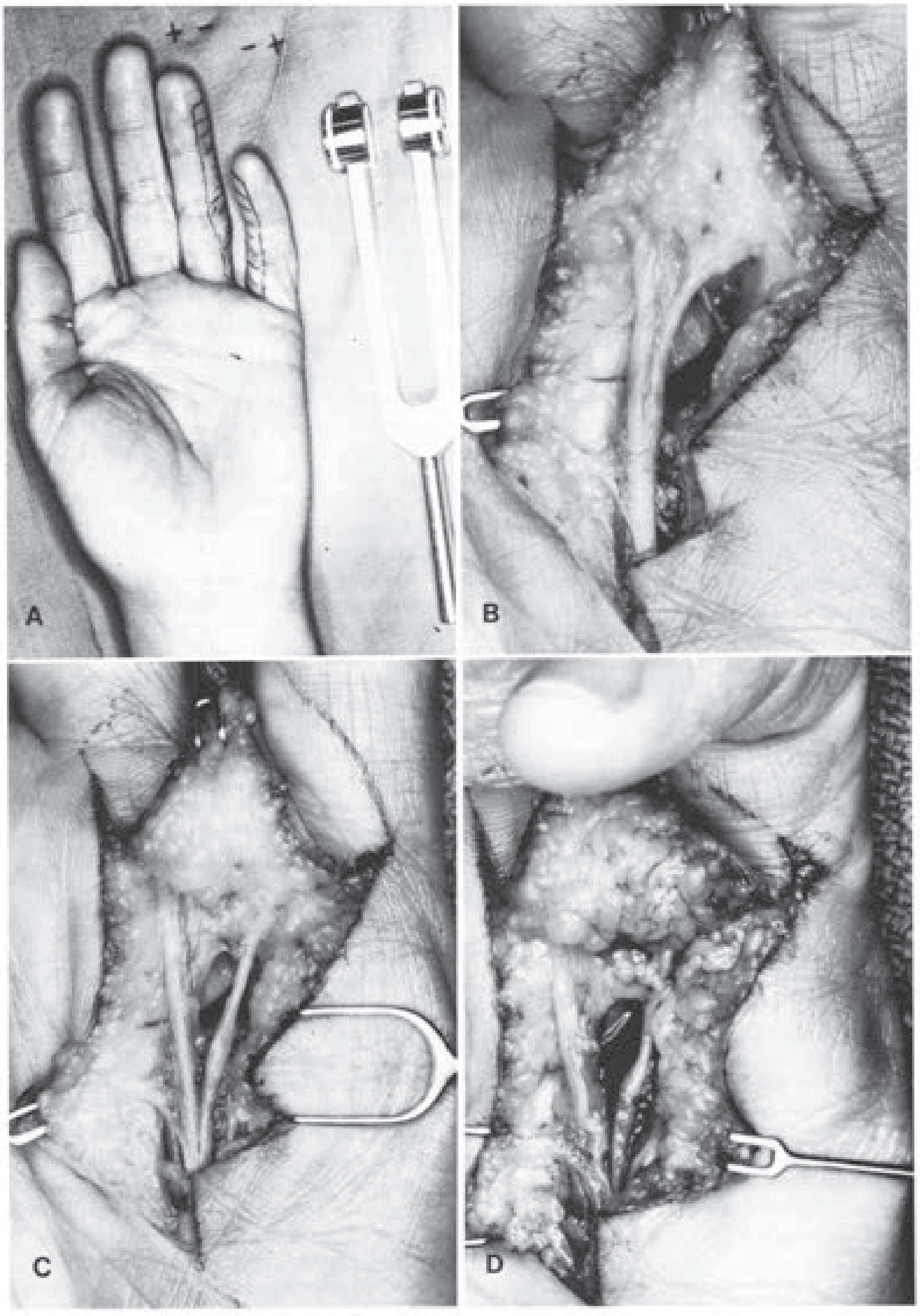


Figure 9.6. Evaluation of potential acute nerve injury. Puncture wound to palm with minimal but definite decrease in vibratory perception over ulnar half of ring finger and marked decrease over ulnar half of little finger. *A*, At surgery a large neuroma was found (*B*). Neurolysis of scarred digital nerve to ring and nerve suture to digital nerve to little finger after resection of neuroma (*C* and *D*).

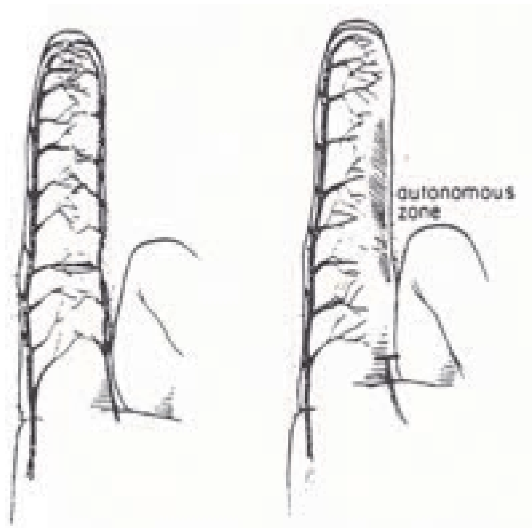


Figure 9.7. Overlap of digital nerve peripheral receptive fields at the fingertip, so that testing at the fingertip, itself, is misleading when evaluating the single digital nerve injury. Test the autonomous zone.

Recall that the peripheral nerve is a mixed nerve having fiber varying in size from 1 to 2 µm (c fibers) to 25 µm. (A-alpha fibers, motor). In the sensory component of the mixed nerve, a very large percentage of fibers are the large, 15 to 20-µm. A-beta fibers, the "touch fibers." When a local anesthetic is injected around a mixed nerve, it crosses the epineurium via diffusion, and via diffusion into each component nerve fiber. The thinnest nerves are therefore affected first, and, as each surgeon has usually had a chance to learn for himself, the first perceptions lost are those related to the thinnest fibers, temperature and pain. Loss of "touch", movement, and pressure are the last perceptions to be lost (see Fig. 9.10.)[59]

When neural ischemia is produced by an upper arm tourniquet, for example, oxygen tension is reduced in the vessels supplying the nerve. The oxygen gradient from inside the vaso nersovum to the axoplasm decreases. The large nerves, with more axoplasm, are affected by the decreased gradient sooner than the thin nerves, whose smaller diameter allows the available oxygen still to supply its needs at a time when the large fibers cease to function. Thus with ischemia, the first perceptions to be lost are those of the large fibers touch. Pain perception is lost last. The patient experiences "pins and needles"[60] (see Fig. 9.10).

When direct pressure is applied to a nerve, the overall force applied to the epineurium is distributed throughout the fascicles to the axons within. Some unequal distribution will occur as a gradient from directly beneath the two pressure points toward the nerve areas farthest away. But within a given fascicle, the largest axons will directly press upon the nearest axon neighbor. Large axons will abut large axons, creating, at least at the initial pressure gradient levels, microinterstices. Within the small sheltered spaces will lie then the thinnest nerves (see Fig, 9.10). Thus with direct pressure upon a nerve, the first perceptions to be lost should be those of the larger nerves: touch. Pain perception should be lost last. Indeed, experimental and clinical observations support this sequence.[61, 62]

It may be argued that direct pressure on a nerve has its effect, in pathogenesis, by diminishing blood flow (Fig. 9.10). Direct pressure induces neural ischemia. This is the postulated mechanism in the acute compartment syndrome.[63, 64] However, the critical observation coming from this pathoneuro-physiology, is that with compression neuropathy, acute or chronic, the first sensory component to become affected and therefore the first perception to become altered is touch, not pain. We should direct our diagnostic testing not with a pin or needle, but with techniques to evaluate the perception of touch. I suggest the tuning fork.

Carpal Tunnel Syndrome

The clinical presentation and anatomical basis of the carpal tunnel syndrome are well known and have been described extensively, if not exhaustively. Perhaps the most torough and well referenced treatment of this subject is Spinner's.[65]

The purpose of this section is to present the value of vibratory testing in nerve compression problems beginning with the most common. I believe that abnormal vibratory perception in the thumb and/or index finger in comparison to ipsilateral little finger is the earliest possible nonprovocative sign (and often positive when the provocative signs are negative) in the carpal tunnel syndrome and therefore deserves a place in the clinical examination.

Comprehensive sensibility evaluation was performed on 36 patients with a history compatible with the carpal tunnel syndrome.[42] In 28% of these patients, perception of vibratory stimuli was equal (normal) in the thumb and index finger of the affected hand in comparison to the ipsilateral little finger and contralateral digits (see Table 9.4). In this group with normal vibratory perception, both the classic and moving two-point discrimination were normal (except for one patient with increased *motor* latency). The provocative type examinations demonstrated a normal Tinel's sign (negative Tinel) in 90% and a normal Phalen's test (negative Phalen) in 60% of this group (see Table 9.4).

In 72% of the patients with a history compatible with the carpal tunnel syndrome, there was an abnormal perception of vibratory stimuli. In this group, both classic and moving two-point discrimination were normal in 50% of the patients. In those patients with abnormal vibratory perception who were evaluated further, Phalen's test was negative (normal) in 30%, Tinel's sign was negative (normal) in 39%, and electrodiagnostic studies were normal in 37% (see Table 9.4).

Was either of the two tuning forks more discriminatory or less ambiguous than the other? No. Because it is smaller and, therefore, easier to use, the 256-cps tuning fork would appear to be the more preferable testing instrument.

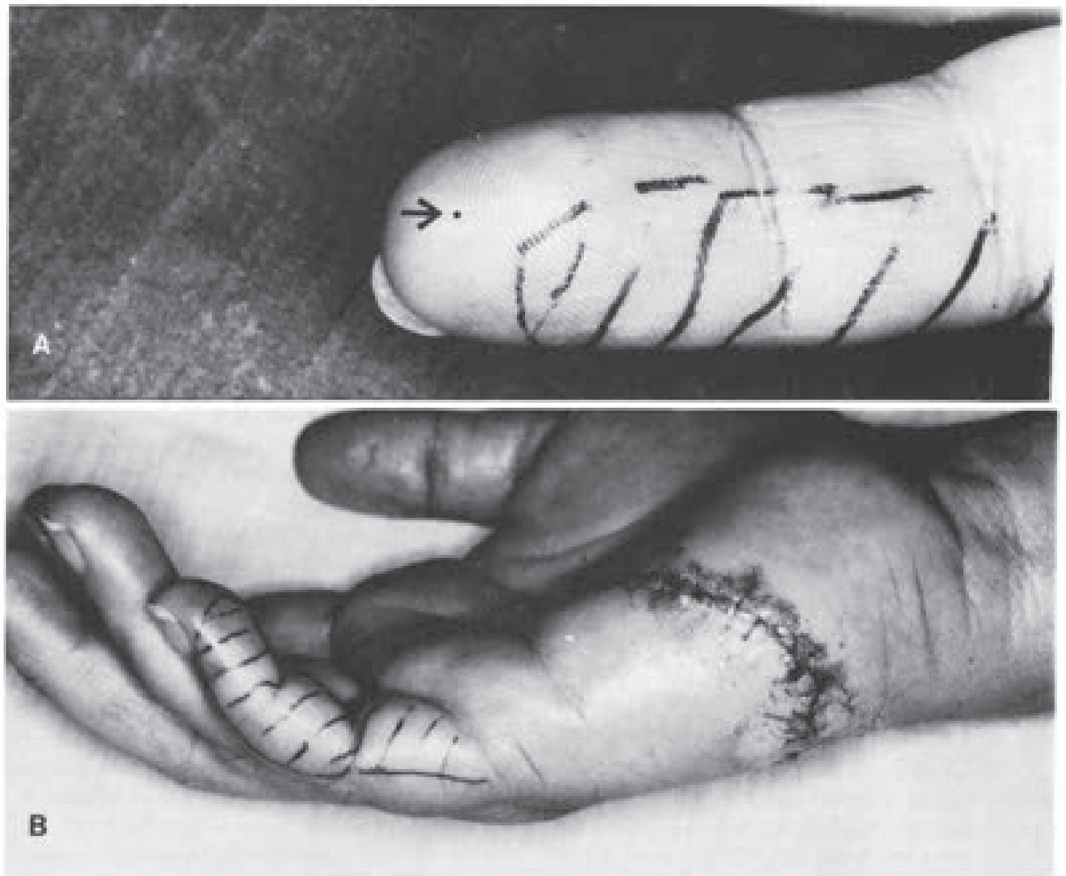


Figure 9.8. Evaluation of potential acute nerve injury. *A*, Note dot at fingertip pulp where first examiner found a normal response to needle stick and pronounced the digital nerve intact. Vibratory perception over autonomous zone was abnormal. *B*, Note sutured hypothenar laceration and outline of sensory defect. At exploration there was complete division of digital nerve to ulnar side of little finger.

All the patients studied following release of the carpal tunnel syndrome demonstrated return of vibratory perception to normal.

Cubital Tunnel Syndrome

The purposed of this section is not to describe the cubital tunnel syndrome, its pathogenesis or operative care. Again Spinner's[66] description is encyclopedic. I wish to emphasize here that vibratory testing has the potential to improve early diagnostic accuracy in peripheral compression neuropathy. Certainly when the patient presents with a hollowed thumb/index web space, or protruding metacarpal shafts with a carrot-tipped little finger ulnar problems no only immediately are apparent but also are usually beyond the help of surgical decompression.

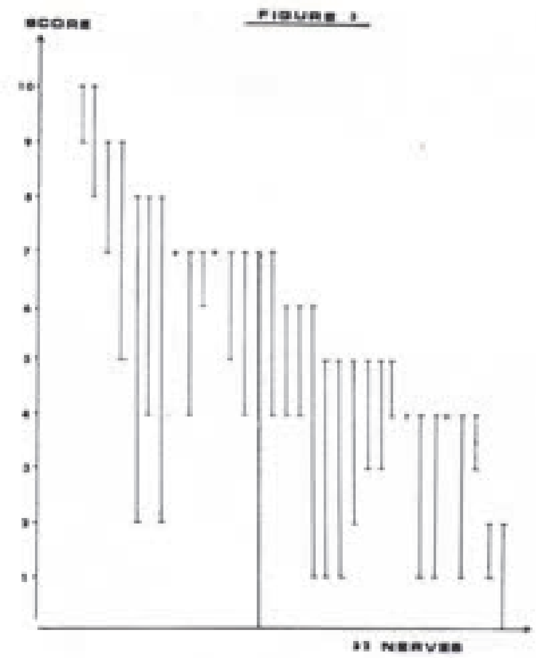


Figure 9.9. Demonstration of digital nerve overlap at fingertip. Note drop in "sensory score" (which included two-point discrimination) in 28 of 32 patients after single digital nerve block. (Reproduced with permission from E. C. Weckesser: Clin Othop 19:200-207, 1961.[54])

My earlier observation,[42] that vibratory perception is diminished in the little finger in contrast to the thumb volarly and over the ulnar half of the hand in contrast to the radial half dorsally, has been confirmed without exception in our subsequent cubital tunnel patients. The return of vibratory perception to normal heralds the recovery of tactile discrimination. The finding over the dorsum of the hand is critical since it localizes the compression to a site above the wrist, and in my experience is usually present (or becomes abnormal) before weakness in the flexor profundus to the little finger.

Acute Compartment Syndromes

By acute compartment syndrome is meant the relatively sudden occurrence of a rise in pressure in a closed space through which space passes a nerve. If a leukemic has a bleeding episode within the carpal canal, an acute carpal tunnel syndrome results. This would be rare. Probably the most common use refers to the posttraumatic rise in pressure due to bleeding, for example, in the anterolateral compartment of the lower leg, often associated with fibula fracture. In the upper extremity, rapid pressure rises can, most commonly, place the median nerve in the forearm in jeopardy. Mechanisms are missile injury, crush, bleeding (brachial artery punctures for blood gasses), etc. In the wrist, of course, and in the small spaces of the hand, pressure rises also place the enclosed nerve in potential danger. Prolonged pressure rise will stop circulation, with ischemic damage to muscle, and ultimately with soft tissue loss. For the purposes of this discussion, the burn (extracellular fluid extravasation beneath an eschar) is included as an acute compartment syndrome.

Diagnosis of a compartment syndrome is taught traditionally to be made by the combination of symptoms and signs that include pain in the compartment, pain in the muscles passing through the compartment when insertion e.g., toe, is moved (passive muscle stretch) loss of arterial pulses distal to the compartment, e.g., dorsalis pedis, and diminished “sensation”, e.g., pin prick. However, based on the foregoing discussion, it should be clear that this traditional diagnostic complex is composed of relatively “late” signs and symptoms. The earliest symptom theoretically should be paresthesias distal to the compartment, coupled with pain or a sense of fullness within the compartment. The earliest sign should be diminished perception touch which, I believe, in the conscious patient is best evaluated with vibratory stimuli. Interesting in this regard is the observation of Salisbury et al.[67] that digital survival following escarotomy in burned hands correlated better with diminished sensibility than with decreased digital artery (Doppler) flow.

The present state of the art, when a compartment syndrome is suspected, is to directly measure the intracompartmental pressure. Excellent techniques to measure the pressure, documented both experimentally and clinically, have been described recently.[68-73] All of these techniques are invasive and require varying degrees of sophisticated monitoring. However, a simple compartment pressure, close enough to reality to make the decision regarding surgical intervention, can be made by Whitesides' method.[68] Of critical importance to our thesis are the observations[69, 71] that diminished “touch and pain” preceded passive-stretch muscle pain and distal pulse loss and paralysis in the progression of the compartment syndrome (see Fig. 9.11)

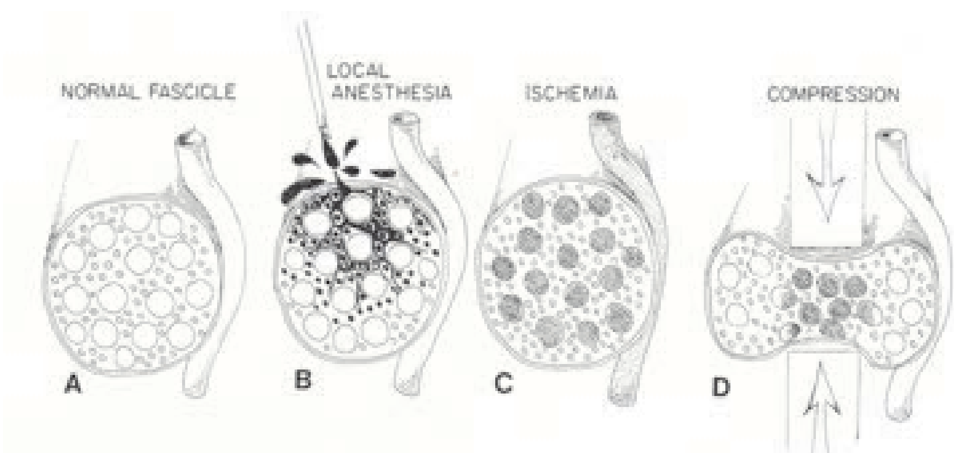


Figure 9.10. Relationship of fiber diameter to sequence of sensory loss. *A*, The normal nerve is composed of a wide spectrum of fiber diameters. With local anesthetics (*B*) or ischemia (*C*), the diffusion effect is paramount. Large fibers are the last to be affected by anesthetic and the first to be affected by decreased oxygen concentration. With direct compression (*D*), these fibers are initially sheltered from the force by the larger fibers. Thus, with pressure or ischemia, touch and vibratory perceptions are diminished first, and pain and temperature perceptions last. The reverse is true with local anesthetics.

Table 9.4
Carpal Tunnel Syndrome

Normal Values	Vibratory Perception	
	Normal	Abnormal
Provocative tests		
Phalen's sign	60%	30%
Tinel's sign	90%	39%
Electrodiagnostics		
Sensory latency	100%	37%
Two-point discrimination		
Classical	100%	50%
Moving	100%	50%

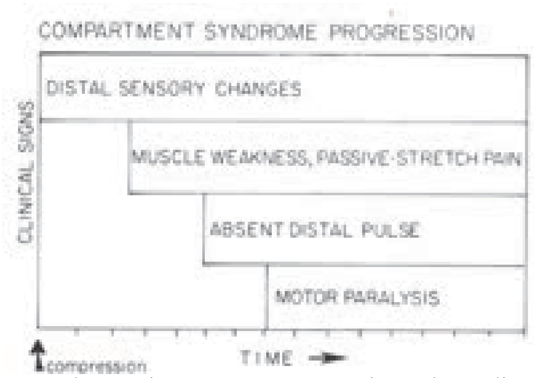


Figure 9.11. Compartment syndrome sign-symptom progression. The earliest symptoms are pain in the compartment and numbness and tingling distal to the compartment. The earliest sign is diminished touch perception, best tested with vibratory stimuli.

Preliminary observations on the use of vibratory stimuli to evaluate acute compartment syndromes in the upper extremity support the thesis that the tuning form evaluation can make an early diagnosis.[42]

Nine patients with potential for acute onset of median nerve compression at the wrist were evaluated. All demonstrated altered vibratory perception. As examples, consider first two burn patients in whom the extremity burns were extensive. One patient had no perception of vibration on admission; escarotomies were done without recovery of vibratory perception (see Fig. 9.12). In this patient, all digits were lost. The other burn patient (see Fig. 9.13) had normal vibratory perception on admission, but during the fluid resuscitation phase had increased extremity swelling. The vibratory perception became diminished. Escarotomy and release of the carpal tunnel were performed with subsequent return of normal vibratory stimuli. Ultimately there was survival of full digital length in all fingers.

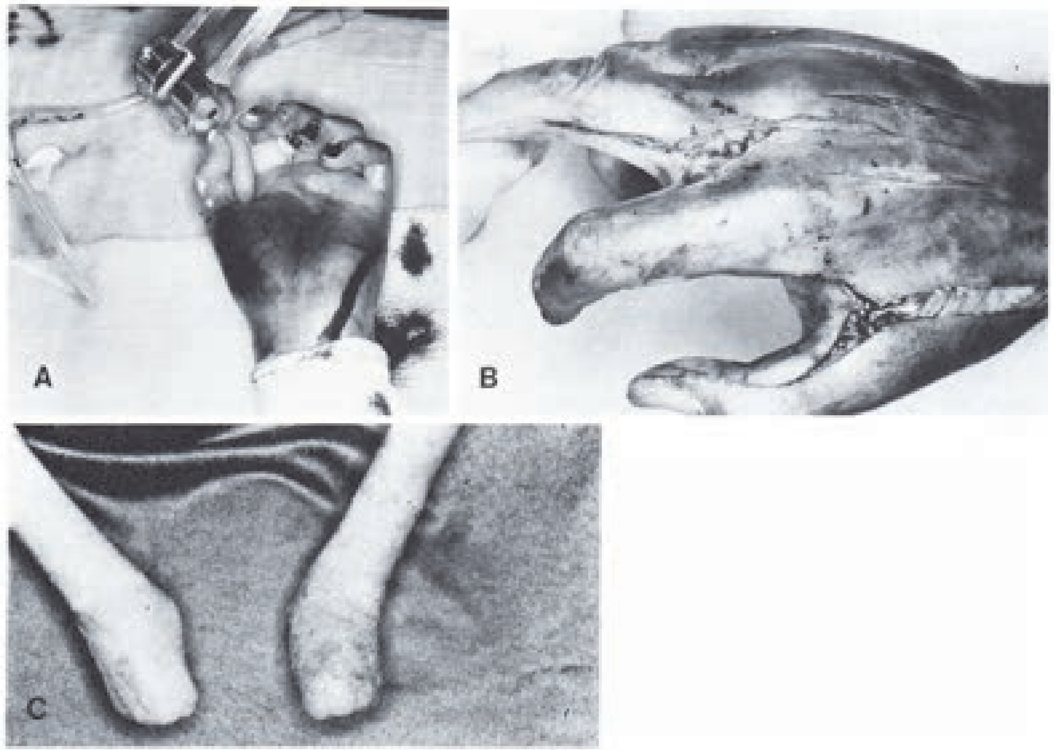


Figure 9.12. Acute compartment syndrome: burn. *A*, Initial absence of vibratory perception in severe burn. *B*, No recovery of perception postescarotomy. *C*, Ultimate full digital loss bilaterally.

Perhaps most important is the inference from the early observations[42] that a progressive diminution in vibratory perception might be used as a guide to time surgical intervention in the evolving acute compartment syndrome.

If perception of vibratory stimuli became abnormal at or before the critical increase in compartment pressure was recorded (and the exact pressure level remains a debated issue) then perhaps those who are either not familiar with the techniques or don't want to use an invasive technique would have a reliable alternative, i.e. the tuning fork. I have already initiated the clinical study to determine this correlating perception of vibratory stimuli with compartment pressures in our patients, and include here the first three patients.

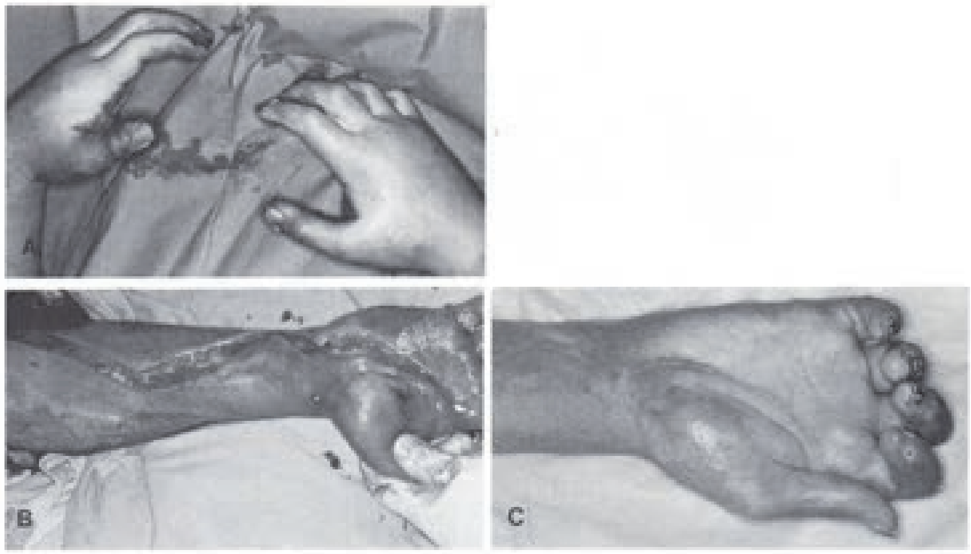


Figure 9.13. Acute compartment syndrome: burn. A, Initial good vibratory perception was lost during fluid resuscitation and escarotomy was performed *(B)*. Ultimate full digital salvage (*C*).

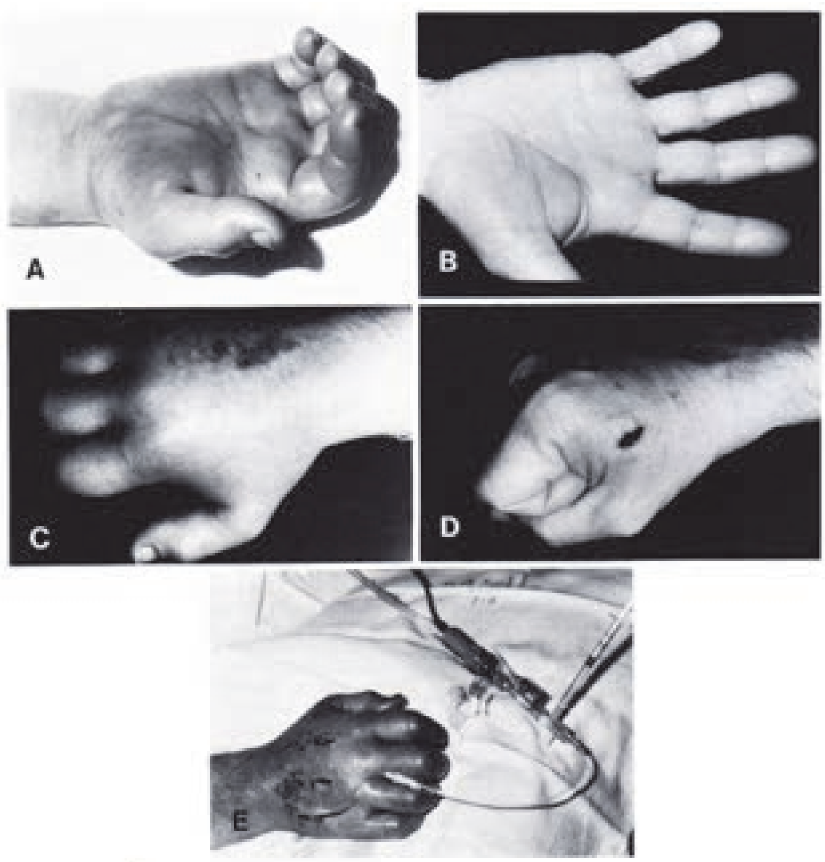


Figure 9.14. Correlating compartment pressure and vibratory perception. Before (*A* and *C*) and 1 week after (*B* and *D*) fasciotomy in a man who developed ischemia of his right hand in the immediate period following coronary bypass surgery. The right radial artery had been catheterized before the cardiac surgery and there was impending gangrene. Vibratory stimuli could be perceived but were abnormal in comparison with the left hand. *E*, Apparatus used for pressure monitoring.

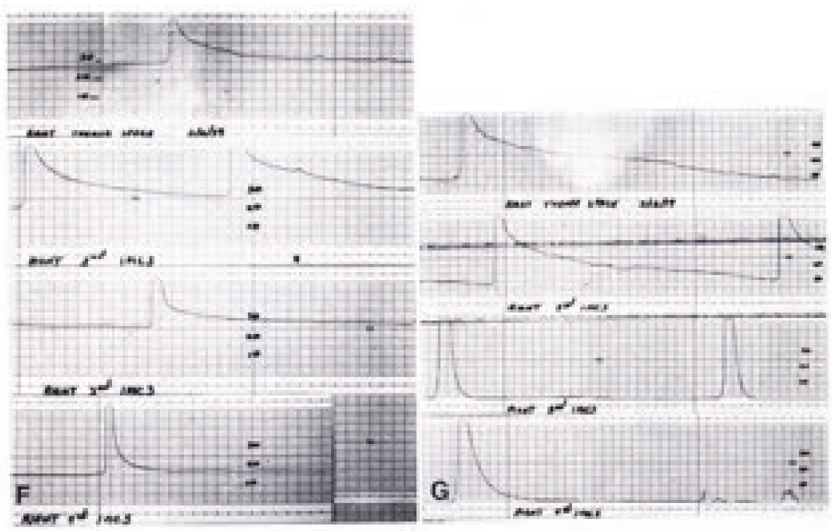
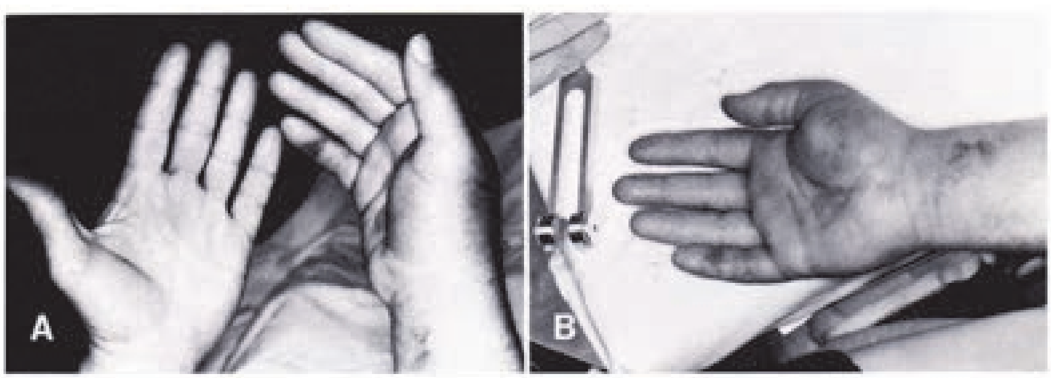


Figure 9.14. *F*, Pressure tracings before and (*G*) 8 hours after fasciotomy. Pressures dropped from 30 mm Hg. to 0 to 10 mm Hg. There was no tissue loss and full function restored. (Reproduced with permission from N. W. Kingsley: Plast Reconstr Surg 63:404-408, 1979.[72]



Time Postcrush	Perception of:			Compartment Pressure (mm Hg)		
	Needle Stick	256 cps	m2PD (mm)	Hypothenar	Thenar	Carpal Tunnel
24 hr	+	↓↓	>10	2	40	45
30 hr	+	↓	8	0	28	35
48 hr	+	nl	4	0	5	10
2 wk	+	nl	2	—	—	—

Figure 9.15. Correlating compartment pressure and vibratory perception. *A*, Ecchymotic and edematous right hand and wrist 24 hours after crush injury. *B*, Evaluation of sensibility. Note pain perception was always present. Vibratory perception was greatly reduced initially over thumb and index finger while normal over little finger. Compartment pressures were elevated in thenar eminence and carpal tunnel. Patient responded to continuous elevation of the hand with the clinical improvement noted in chart.

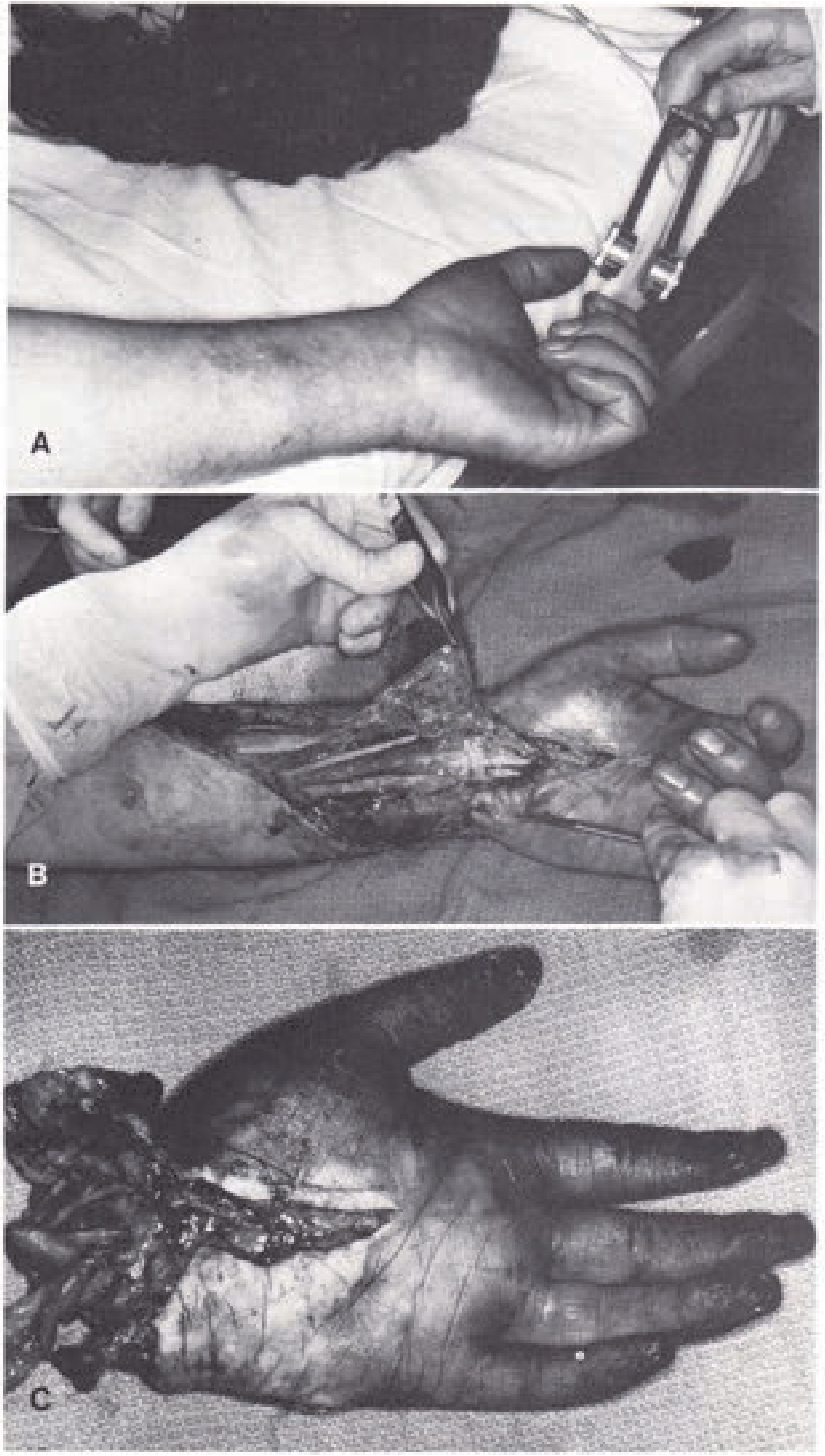


Figure 9.16. Correlating compartment pressure and vibratory perception. *A*, Drug addict 24 hours after brachial artery injection. There was no peripheral pulse, no perception of pain or vibration, and the hand was cold, swollen and bluish. Compartment pressures were 90 to 100 mm Hg and extensive fasciotomies were done (*B*). Gangrene developed, necessitating amputation (*C*).

For the first patient (see Fig. 9.14). I thank Doctor Larry Leonard who, at the time the chief resident in plastic surgery at Johns Hopkins Hospital. For the third patient (see Figure 9.16), I thank

Doctor Russell Moore, who, at the time the patient was studied, was the Hand Fellow at Union Memorial Hospital's Raymond M. Curtis Hand Center.

The first patient was noted to have a markedly swollen, purplish and painful hand on the day following a coronary bypass procedure. The radial artery had been catheterized prior to the procedure to provide monitoring and the catheter removed in the intensive care unit prior to the hand becoming swollen. Because of the patient's critical condition, intraoperative exploration of the radial artery and pharmacologic manipulation of the peripheral vascular system were not possible. The patient had diminished (abnormal) vibratory perception. Compartment pressures were obtained in which the I.C.U. pressure gauges are connected to the compartment, a small bolus of sterile saline injected into the compartment, and the pressure read at equilibrium. Pressures were 30 mm HG and, in this low cardiac output state, were considered elevated. Dorsal space fasciotomies were done with good release of the pressure and ultimate full tissue and hand function salvaged (Fig. 9.14).

The second patient (see Fig. 9.15) sustained a crush injury to his right hand and wrist 24 hours prior to his emergency consultation. On examination, he had a grossly swollen and ecchymotic palm and volar forearm. He had greatly diminished vibratory perception over his thumb, index and middle fingers. Pain perception was still intact. Release of his carpal tunnel was advised and was refused. I elected then to follow him with compartment pressures while elevating his hand Tuning fork perception improved concomitant with a decrease in compartment pressure. Over the next month, he recovered normal sensation

The third patient, a drug addict, was seen to the emergency room 24 hours after the onset of hand pain. On examination, there were recent injection sites in the antecubital fossa, the hand was cold, swollen, bluish, and without radial or ulnar pulses. There was perception of pain on vibratory stimuli (Fig. 9.16). Compartment pressure in the forearm and carpal tunnel were 90 and 100mm HG. Despite extensive fasciotomy, the hand became gangrenous, requiring amputation

These three cases suggest that vibratory perception become abnormal when the pressure in the compartment surrounding the nerve reaches 35 to 40 mm Hg. This is the pressure at which most advocates of compartment pressure monitoring are advocating fasciotomy. Further clinical experiences with these correlations are, of course, needed. Furthermore, I am now directly investigating this in an animal model.

VIBRATORY TESTING

TUNING FORK ADVANTAGE

The tuning fork offers a significant advantage to the clinician evaluating a potential nerve injury. For example, I the child it has been observed that "lacerated nerves are frequently missed" and that sensory loss is "difficult to test for."[74] The tuning fork, perceived by the child as a musical sounding toy, is readily accepted; the usual pin produces fear, if not future distrust. Once the tuning fork is introduced to the child, you simply obscure his view with your hand and apply the tuning fork: his perception of the vibration is signaled by a hand movement or a laugh. Another example is the emergency room encounter with the noncooperative, usually drunk, male patient. In this situation, a needle frequently evokes hostility while the tuning fork's vibrations seem to penetrate the inebriated stupor. In situations where repetitive testing is required, such as evaluating the progress of a nerve repair or recovery from neuropraxia, the tuning fork is an easily applied, noninvasive technique with high patient acceptance. Furthermore, vibratory stimuli are not ambiguous as it is the rare patient who has felt them before. Vibratory stimuli allow you to avoid the situation where you are touching a patient's finger following nerve repair and asking him if he feels your touch. Because the regenerating sensory fibers are often misdirected and always deficient in number, the patient may not interpret the altered profile of neural impulses he is receiving in a manner that lets him answer "yes" to your question. Since he may have no previous memory in his association cortex with which to identify this altered neural profile as "touch," he often will incorrectly answer a question calling for an identification even though sensibility has been recovered. Vibratory stimuli circumvent this problem.

POTENTIAL PITFALLS

As with all diagnostic tests, the tuning fork has potential pitfalls. There are three. First, when evaluating a digital nerve, it is critical that the examiner ask the patient not whether he "feels anything" but whether he "feels the same thing on each side (not the tip) of the finger. If the patient answers "no", then the examiner must pursue the questioning with "how do they differ?" A "positive" test, indicating blocked nerve conduction in the examined nerve, is indicated by the patient's decreased perception of the vibratory stimulus. If the possibility exists that both digital nerves have been injured in the finger, and the patient perceives the stimulus, it is then critical to compare this perception to the contralateral digit in the case of nerve compression at the wrist, where the perception over the thumb and index are compared to that over the little finger, the contralateral fingertips must be tested for comparison because of the possibility of both median nerve and ulnar nerve compression.

The second potential pitfall is that perception of the stimuli may occur through an adjacent peripheral field of a noninjured nerve, e.g., radial nerve with a median nerve injury. The examiner must always conclude by having the patient localize the stimulus perception. Where did you feel that?" If the patient points to the dorsal surface of the proximal phalanx of the index finger or thumb when you are testing in the territory of the median nerve, this "perception" should, obviously, not be considered normal. Such events occur, as discussed earlier because the tuning fork sets up a traveling wave within the substance of the entire finger and this wave may have sufficient energy to stimulate receptors at a distance from the test area. Careful discrimination by the examiner can avoid these potential pitfalls.

Finally, the alteration in vibratory perception is not always a diminution. As I have been examining increasing numbers of patients with early nerve compression problems, I find that often the alteration is one of *hyper*sensitivity. For example, a patient with carpal tunnel symptoms of short duration may observe that the feeling caused by the tuning for touching the thumb is "more sensitive" or "more electric." It is therefore possible that early in the course of neural ischemia a state of sensitivity. For example, a patient with carpal tunnel symptoms of short duration may observe that the feeling caused by the tuning for touching the thumb is "more sensitive" or "more electric." It is therefore possible that early in the course of neural ischemia a state of *hyper*esthesia is present. The critical examiner must be aware of this possibility

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Chapter 10

EVALUATION OF SENSIBILITY IN THE HAND

I am quite convinced that physiology alone, unaided by clinical observation, would be very slow in unraveling the mysterious functions of the nervous system.

M. von Frey, 1906[1]

INTRODUCTION

TESTING FUNCTIONAL SENSATION

EVALUATION

INTRODUCTION

Many tests have been described to evaluate sensibility in the hand (Table 10.1). On what basis should we select the tests to use? I suggest that our goal is to evaluate hand sensibility within the framework of rehabilitation of the hand. Our goal is not to localize a lesion within the central nervous system. The main distinction here is that tests must be chosen that have a neurophysiologic basis and that have been demonstrated to correlate with hand function (Table 10.2).

Table 10.1
Evolution of Clinical Tests of Hand Sensibility [a]

...	Unknown	Pin stick, hot/cold, sweating, finger stroking, cotton wool, paper strips, blunt/sharp
1835	Weber	Two-point discrimination
1852	Valentin	Cogwheel
1894	von Frey	Tactile hairs, pain hairs
1909	Trotter, Davies	Localization[b]
1915	Tinel	"Tingling"
1915	von Frey	"Vibratory hairs"
1928	Minor	Starch iodine[c]
1929	Henney	Pallesthesiometer
1943	Seddon	Digit writing[d]
1945	Seddon	Coin test (after Ridoch)
1956	Dawson	Sensory nerve conduction velocity
1958	Moberg	Pick-up test, tactile gnosis Ninhydrin Paper clip
1960	Semmes-Weinstein	Monofilaments
1966	Parry	Timed recognition test
1966	Porter	Letter test
1969	Renfrew	Depth-sense aesthesiometer (Poppen's "plastic ridge", 1979)
1972	Dellon	Constant-touch, moving-touch, tuning forks, 30 and 256 cps
1973	O'Rian	Palmar skin wrinkling
1978	Dellon	Moving two-point discrimination

[a] All references for these tests other than those specified may be found in their appropriate book chapter through the index and in the combined bibliography.
[b] Reference 35.
[c] Reference 36.
[d] Reference 37.

Table 10.2
Neurophysiologic Basis of Sensation

Sensation	Clinical Test	Neurophysiologic Correlate	Peripheral Receptor	Nerve Fiber Property
Constant-touch	Fingertip touch	Stimulus	Merkel cell-neurite complex	Slowly-adapting
Pressure	von Frey hair	Threshold		
Tactile gnosis (static)	Classic two-point discrimination	Innervation density		
Moving-touch	Fingertip stroking	Stimulus	Meissner corpuscle	Quickly-adapting
Flutter	30-cps tuning fork, vibrometer	Threshold		
Tactile gnosis (moving)	Moving two-point discrimination	Innervation density		
Moving-touch	Fingertip stroking	Stimulus	Pacinian corpuscle	Quickly-adapting
Vibration	256-cps tuning fork, vibrometer	Threshold		
Tactile-gnosis (movement)	Moving two-point discrimination	Innervation density		

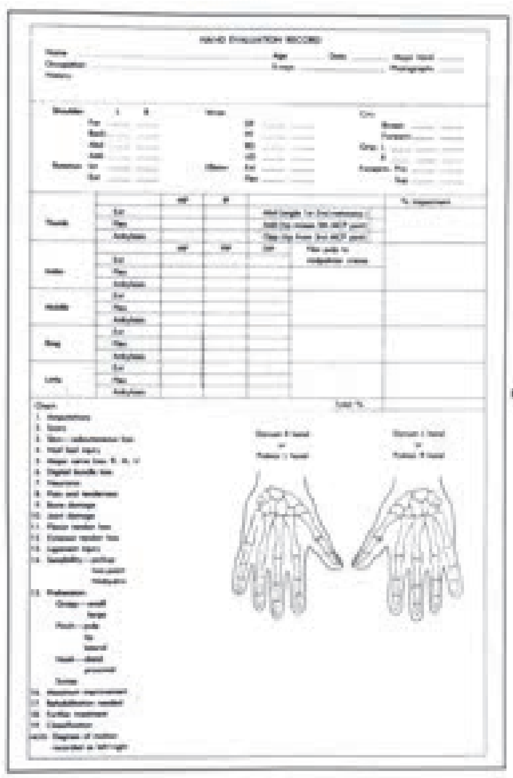

Figure 10.1. A comprehensive approach for evaluating hand function. Evaluation of sensibility is dominated here by the emphasis on motor function. (Reproduced with permission from A. B. Swanson et al: *Rehabilitation of the Hand*, Hunter JM et al (eds). Saint Louis: CV Mosby, 1978.[5])

The results of testing for the perception of pain or for the perception of temperature indicate whether protective sensation is present and whether the spinothalamic tracts are intact. Testing for perception of pain and for perception of temperature does not correlate with ability to perform hand functions such as sewing on a button or winding a watch. Tests of pain and temperature are, therefore, "academic" and do not measure functional sensation. Tests of sudomotor function also do not correlate with hand function. If a nerve is divided, all sensory submodalities are affected. If a nerve is repaired with even a small degree of accuracy, sweating and perception of pain and temperature virtually always recover.[2,3] I suggest, therefore, that valuation of sensibility of the hand, within the framework of hand rehabilitation, need not include tests of sudomotor function, pain or temperature perception.

I suggest that evaluation of sensibility of the hand, when the goal is: (1) diagnosis of a peripheral nerve injury or compression neuropathy, (2) evaluating recovery following nerve repair, (3) initiating sensory re-education, or (4) determining functional impairment, may be defined as evaluation of the fiber/receptor systems that mediate the perception of touch. The approach to be outlined below is highly efficient in terms of testing time and valid terms of its neurophysiologic basis and functional correlation.

To put this approach into perspective, one need only review the most recent four attempts to detail evaluation of hand function.[4, 7] There is some attempt to orient hand evaluation by ultimate goal. For example, the approach by Swanson et al,[5] is comprehensive, yet clearly oriented toward the motor aspects of hand function. One of their 19 items of clinical information pertains to sensibility, and this item subdivides into the pick-up, two-point, and ninhydrin test (Fig. 10.1). These tests are described in two paragraphs of a 38-page chapter and described under the heading of "neurologic examination." Furthermore, the definition of sensory impairment is "complete loss of palmar sensation" This implies that presence of just protective sensation, that is absence of tactile gnosis, would not be evaluated as impairment of sensation. Fess et al.[6] present a beautifully outlined, balance approach to evaluating hand function, in which sensibility is given detailed consideration. Their hand charts (Fig. 10.2) require evaluation of classic two-point discrimination, moving-touch, constant-touch, 30-cps and 256-cps vibratory stimuli, Tinel's sign, von Frey hairs, pain and temperature perception, proprioception, hypersensitivity, and the Moberg pick-up test. This comprehensive program is similar to one utilized to evaluate the nerve-injured servicemen recovering from war wound and reported by Omer.(4) Omer reported 26,900 separate tests! These were performed as a matrix of 12 tests repeated every 6 weeks in the initial phase of sensory recovery. Critical to Omer's approach was the determination of cutaneous pressure thresholds with Semmes-Weinstein monofilaments and classic two-point discrimination with a Boley gauge or eye calipher.[8‡] Judith Bell who also relies heavily on Omer's schema, conceptualized the problem well.[7] She wrote, "What is desired is a simple test that can be easily and reliably performed in a variety of clinical setting. Many are the tests that have been described… Each test gives us a picture of the elusive perception we call (sensation) … It may be wise to trade the idea of a simple test for that of thorough testing." Her approach to evaluating sensibility combines exhaustive Semmes-Weinstein

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‡ It was in this paper that the numerical values of these Semmes-Weinstein monofilaments (these values are really the log[10] [force in milligrams]) were reported erroneously in milligrams (see Chapter 6.)

monofilament and Weber two-point discrimination testing of the hand supplemented by electrodiagnostic testing. This approach approximates ours in that it emphasizes a quantitative evaluation of the touch submodality but differs from ours in two critical ways: (1) it is limited to the slowly-adapting fiber/receptor system, the smallest subpopulation of the touch spectrum; and (2) it stresses determinations of threshold values in preference to innervation density (Fig. 10.3).

Testing Functional Sensation

Given a choice of just one test of sensibility with which to evaluate a hand and predict the ability of that hand to function, which test should be chose? To answer this question, a study must both evaluate sensibility and correlate these test results with a measure of actual hand function.

Throughout the past 2 decades, virtually all studies reporting the results of nerve repair, the quality of sensation in various flaps and grafts, and degrees of sensory impairment in nerve compression and neuropathy have reported their end results in millimeters of classic two-point discrimination. The credit for this universal concurrence belongs to Erik Moberg, who, with almost evangelistic zeal, converted pointed caliphers to blunted tips. Moberg resurrected the paper clip from rusting ruin to the Keys of the Kingdom. His clinical investigation, upon which so much of the present-day approach to sensory testing is based, was the first to correlate clinical tests with tests of hand function. Moberg defined hand function in terms of sensory grips. Good hand function implied the presence of tactile gnosis. This meant that with eyes blindfolded, the patient would still "see" with his fingertips. This was measured by his pick-up test. The only test that Moberg found that correlated with the results of this pick-up test was the Weber two-point discrimination test. Moberg studied 10 patients who had median nerve injuries and who, at the time of evaluation had good motor function (Table 10.3).[2] Of these 10 patients, only three had two-point discrimination less than 15 mm. These patients had precision sensory grip and could perform the pick-up test. Five patients had two-point discrimination between 15 and 40 mm. These patients had gross grip, but could not perform the pick-up test. The von Frey measurements did not correlate with hand function. For example, a threshold of 1.0 gm was associated with two-point discrimination values ranging from 5 mm to greater than 40 mm, with corresponding hand functions ranging from precision grip with pick-up test ability to gross grip without pick-up test ability.

On the basis of Moberg's study, a two-point discrimination of less than 12 or 15 mm has been accepted widely as being required for tactile gnosis (precision-sensory grip and the ability to perform the pick-up test). However carefully this group of patients was studied, I must emphasize that there were just three patients reported in that group of patients having good recovery of functional sensation. Furthermore, the standard for hand function was chosen to be a static grip and a (nontimed nonrecognition) pick-up test.

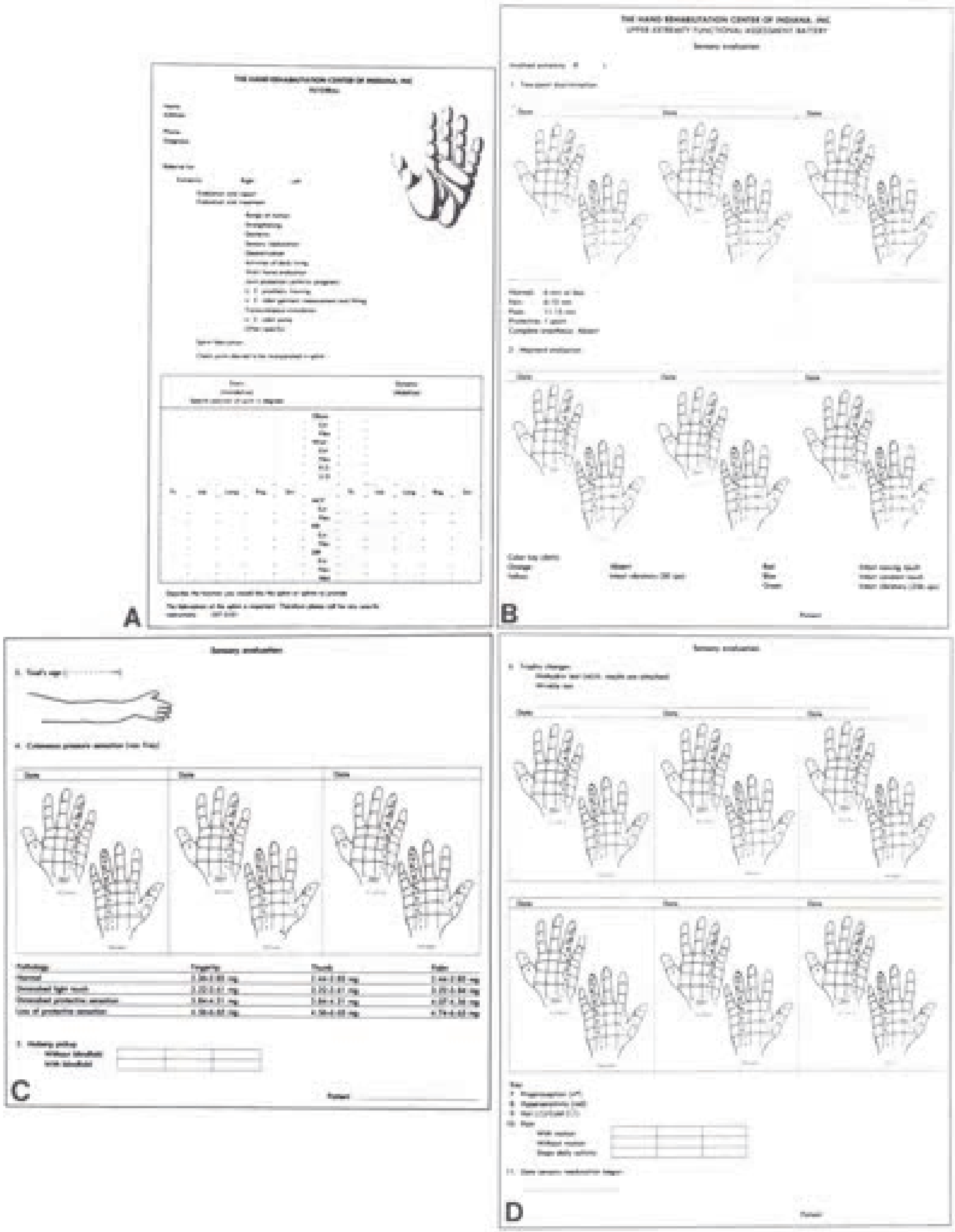


Figure 10.2. A comprehensive approach for evaluating hand function. Evaluation of sensibility plays a prominent role in this balanced approach. (Reproduced with permission from E. E. Fess et al: *Rehabilitation of the Hand*, Hunter JM et al (eds). Saint Louis: CV Mosby, 1978.[6])

Three studies reported at that same time attempted similar correlations of tests of sensibility with tests of hand function (tactile gnosis). These studies have never been quoted at this point as far as I am aware, probably because the emphasis of these reports was end-results of nerve repair. Flynn and Flynn's findings[9] confirmed Moberg's (Table 10.4). Precision sensory grip was present with classic two-point discrimination less than 15 mm. McEwan's data,[10] however, suggested that tactile gnosis, as measured by a blindfolded pick up test, could be even in patients with poor classic two-point discrimination. Onne's comments[3] that the blindfolded pick-up test was normal with a classic two-point discrimination of less than 7, and abnormal if 16 to 22 mm, agree with Moberg.

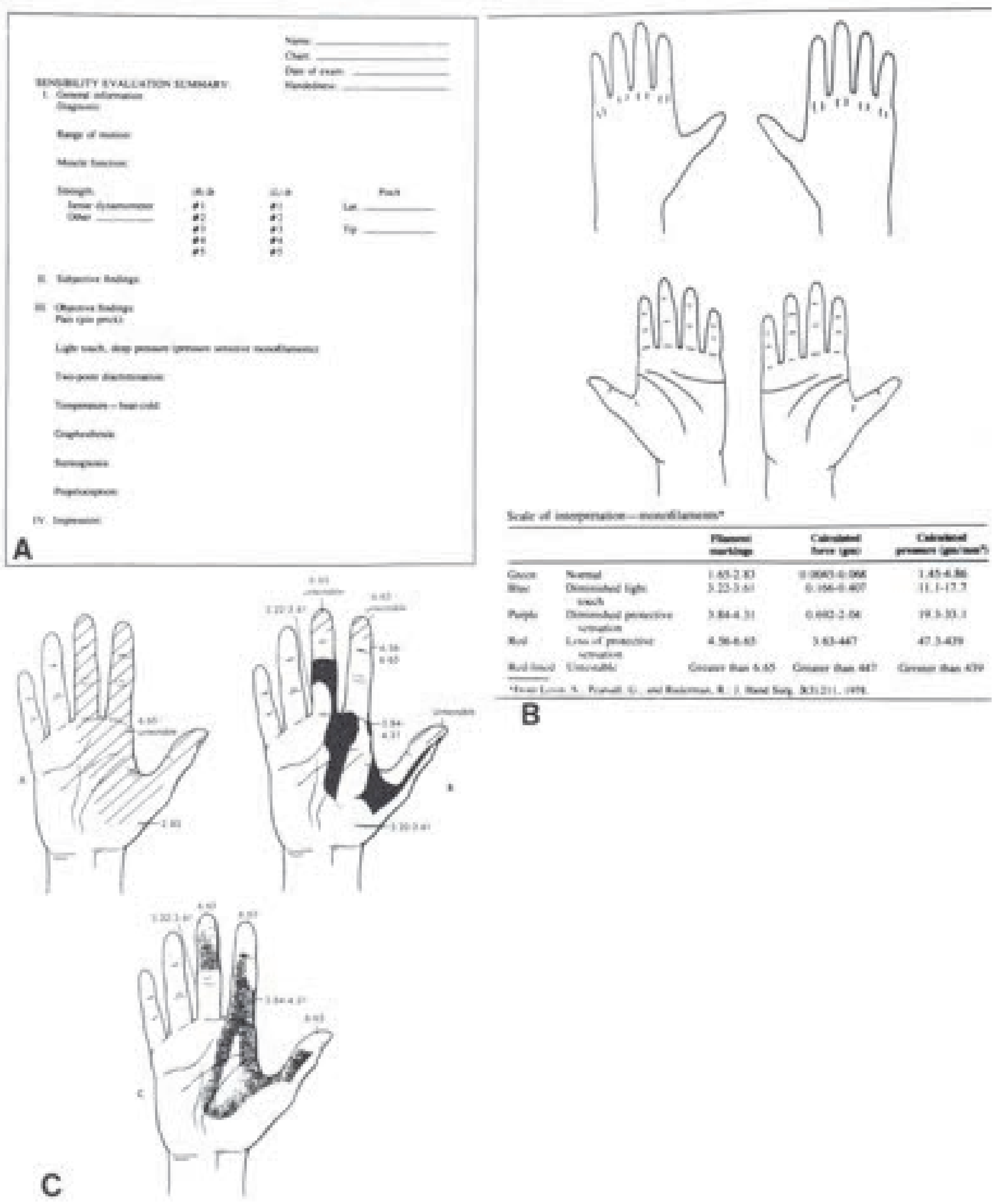


Figure 10.3. A comprehensive approach for evaluating hand function. This approach *(A* and *B)*, in fact, emphasizes primarily the determination of pressure thresholds *(C)*. (Reproduced with permission from J. A. Bell: *Rehabilitation of the Hand*, Hunter JM et al (eds). Saint Louis CV Mosby, 1978.[7])

Among earlier studies, I can find only two case reports correlating tactile gnosis and the Weber text (Table 10.4). Oester and Davis[11] detailed the 10 best results following median nerve repair at the wrist. Case 4452 had classic two-point discrimination greater than 25 mm but could button his shirt and pick-up a pin blindfolded. Case 4266 had a classic two-point discrimination of 4 mm (thumb) and 12 mm (index) and could pull the correct coins from his pocket. Although the latter case supports Moberg's position, the first case and the results of McEwan's[10] suggest that the Weber test may be missing something, that there may be more to functional sensation than static grip.

Porter[12] studied fingertips resurfaced with flaps and grafts, comparing sensibility tests with hand function. He found the results of his letter test correlated better with ability to perform Moberg's pick-up text than did classic two-point discrimination. The average letter test score for those passing the pick-up test was 2.3 compared to 0.9 for those who failed the test. The mean two-point discrimination for those passing the pick-up test was 7.8 mm versus 9.4 for those who failed. No tests of statistical significance were offered. In another correlation of sensibility tests and hand functions done on patients with flaps (neurovascular island flaps), Krag and Rasmussen[13] noted that patients had the ability perform the pick-up test yet had poor two-point discrimination.

There has been a recent study on end-results after nerve injury that also attempted to relate sensibility testing to hand function.[14] In this study a Vietnam serviceman's nine object recognition test was scored and the results correlated with the Weber test during the course of his sensory recovery (Table 10.5). Although with a Weber test of 16 mm or less, he identified most of the objects correctly, he could also identify some objects when he had effectively no classic two-point discrimination.

These types of observations, as discussed in Chapter 8, were part of the stimulus that led me to develop the moving two-point discrimination test.[15] In that study, hand function was related to moving two-point discrimination only in terms of the patients' return to work or to the preinjury level of activity. Specific tests of hand function were not evaluated.

A recent comprehensive report evaluated sensibility after digital nerve suture.[16] Although this study makes conclusions regarding tactile gnosis, it in fact failed to test hand functions. The study did graphically contrast results of von Frey hairs (Semmes-Weinstein monofilaments) with results of the classic Weber two-point discrimination. There was no correlation between these two tests of sensibility (see Chapter 5). For a von Frey range of less than 1.0 gm (their normal threshold value), two-point discrimination ranged from 3 to 32 mm (normal being less than 6 mm). Furthermore, for two-point discrimination values in the 6- to 12 mm range, in which, according to Moberg, tactile gnosis should still be possible, there were many patients with abnormal von Frey values. Onne's data[3] also demonstrated no correlation between results of the Weber test and von Frey test (Table 10.6).

Table 10.3
Correlation of Sensibility Testing with Hand Function[a]

Case	von Frey (gm)		Weber test (mm)		Grip Function		Pick-up Test
	Index	Thumb	Index	Thumb	Gross	Precision	
1	1	1	8	5	+	+	+
2	1	0.5	20	15	+	−	−
3	0.5	0.5	15	12	+	+	+
4	1	0.5	12	12	+	(+)	(+)
5	1.5	1	>20	>20	+	−	−
6	1.5	1	>40	>40	+	−	−
7	2.5	1	>60	15	+	−	−
8	2.5	1.5	>40	>40	−	−	−
9	2.5	2.5	>60	>40	−	−	−
10	2.5	1.5	>40	>40	+	−	−

[a] Adapted from E. Moberg.[2]

Table 10.4
Correlation of Tactile Gnosis and Weber Test after Nerve Repair[a]

Age at Injury (yr)	Follow-up (mo)	Grip Function		Weber Test (mm)		
		Gross	Precision	Thumb	Index	Middle
3	84	++	++	3	3	4
10	24	++	++	6	8	8
23	96	+	+	12	14	16
26	84	+	+	14	12	14
24	72	−	+	12	12	12
16	96	−	−	26	26	26
52	132	−	−	40	40	40
16	24		−	26	26	22

[a] Adapted from J. E. Flynn and W. F. Flynn.[9]

Table 10.5
Correlation of Tactile Gnosis and Weber Test after Nerve Repair[a]

Time after Repair (mo)	Classic Two-Point Discrimination (mm)	Object Recognition
		No. Correct/No. Tried
5	>45	2/9
6	>45	3/9
7	>45	5/9
→[b]		
10	20	6/9
11	16	7/9
12	6	9/9

[a] Patient is 25 years old, with median nerve repair at wrist. (Reproduced with permission from R. L. Reid et al: *Am Soc Surg Hand Newsletter* 15, 1977.

[b] Sensory re-education was begun 8 months after the primary nerve repair.

Poppen et al.[16] used a modified Renfrew depth-sense esthesiometer for evaluating sensibility. This "plastic ridge device" gave values which correlated with neither von Frey hair nor Weber test results. I have explained[17] these findings in light of the neurophysiologic principles discussed in Chapter 3. The Plastic Ridge Device is testing the quickly-adapting while von Frey and Weber test the slowly-adapting fiber/receptor populations. The importance of the Poppen et al.[16] study does not lie in their presentation of a “new test” of sensibility. As discussed in Chapter 8, the Ridge Device is not only based on inappropriate philosophical speculation (there is no somatic senses of space or choraesthesia), but also is poorly calibrated, has a wide range of normal, is difficult to use, and so, is difficult to obtain. They failed to correlate Ridge results with either the pick- up or object identification test, so they cannot make a valid correlation of Ridge results with tactile gnosis. The importance of their work is the further confirmation that tests of threshold (von Frey) do not necessarily correlate with tests of innervation density.

In a given test area the threshold for perception of constant-touch/pressure can be normal if just one slowly-adapting fiber reinnervates the appropriate Merkel cell-neurite complex and this has had time to “mature” prior to testing. In an adjacent area this reinnervation may not have occurred, and the threshold would be abnormal (higher). In such a situation, there would be a low peripheral innervation density, a poor (high) two-point discrimination, but in certain areas of the fingertip, normal threshold values, Onne’s data[3] are also explained by this hypothesis (Fig. 10.4). I believe the slowly-adapting fiber/receptor system is predisposed for this to occur following nerve repair for three reasons: (1) The Merkel cell-neurite complex degenerates more rapidly than its quickly-adapting fiber/receptor system counterpart (see Chapter 4). Therefore, there will be less Merkel cells in an optimal state for reinnervation by the regenerating axon; (2) The ratio of axon to corpuscle in this system is less than one (Merkel cell-neurite complex: <1, Pacinian corpuscle: 1, Meissner corpuscle >1, see Fig. 7.5).Therefore, the chances of a Merkel cell being reinnervated by a regenerating axon is the least likely of the sensory corpuscular endings; and 3) The slowly-adapting fibers comprise only about one-third of the group A beta fibers (see Chapter 3). Therefore, if only a fraction of the proximal axons re-enter distal endoneurial sheaths, and if only a fraction of these are correctly redirected, i.e., to the correct distal locations and to the correct sensory receptor, the actual number of regenerating slowly-adapting axons is more likely to be below the critical number required to give a peripheral innervation density capable of tactile discrimination. To restate this thesis: regeneration favors recovery in the quickly-adapting Meissner afferent system, the system for movement detection.

Moberg recognized that we needed a new test of functional sensation. Delivering the first Sterling Bunnell Memorial Lecture before the American Society for Surgery of the Hand in 1964, he said[18] “The tools are still crude and must be improved.” These concerns have been echoed in 1978 by Narakas,[19] whose sensory evaluation in patients recovering from brachial plexus injuries has demonstrated that “achieved tactile gnosis is not parallel to the clinical tests we have. Good results in the laboratory (clinical examination) can be useless in life and vice versa.” The moving two-point discrimination test was presented to the American Society for Surgery of the Hand in 1978, as a quantitative test which answered the criticisms outlined above and in Chapter 6 of the static Weber test. “Every time we conceive and express quality as quantity, our knowledge increases and along with it our powers of thinking and acting correctly."[20]

The focus on movement has been emphasized most recently (1980) in a review of thumb replantation from Louisville.[21] A comparison was made between results of classic two-point discrimination (sensibility) and the patient's subjective assessment of his sensory recovery (sensation). Patients listed decreased thumb motion highest as the cause of decreased usefulness of their replanted thumb (Table 10.7). The authors concluded "that greater than 10 mm or two-point discrimination is compatible with good sensation: and that these findings indicate that "motion, as well as sensibility, is important in the replanted thumb." The static thumb cannot use its movement detection system.

Table 10.6
Absent Correlation Between Weber and von Frey Testing[a]

Nerve	Von Frey (gm)	Weber Range (mm)
Digital	0.3	2–18
	1.0	7–25
Median	0.3	2–27
	1.0	6–30

[a] Adapted from L. Onne.[3]

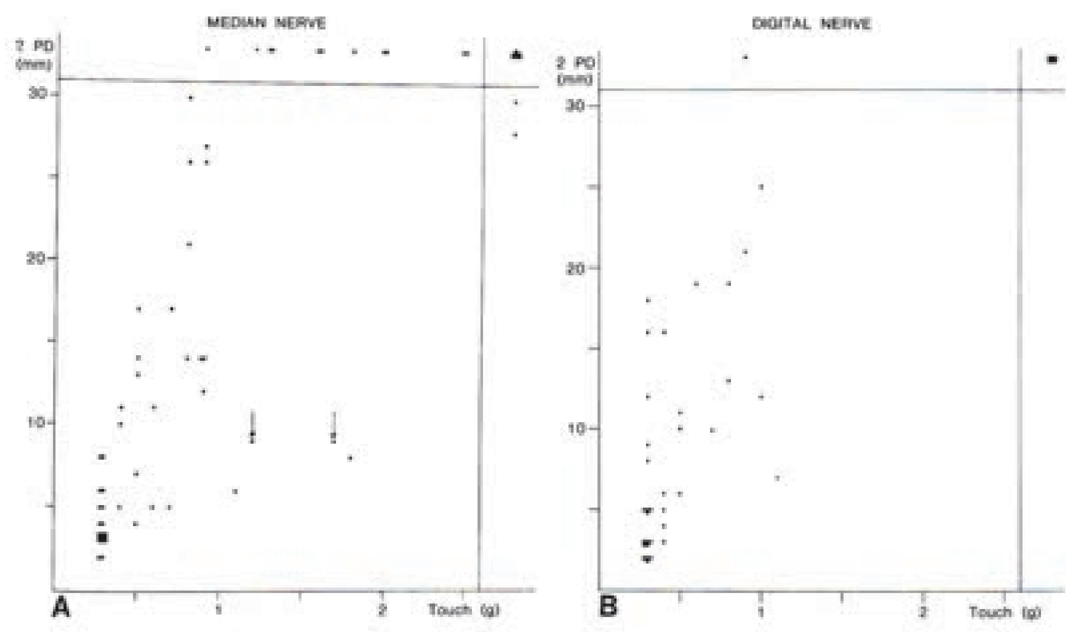


Figure 10.4. Lack of correlation between von Frey hairs and classic two-point discrim-

Figure 10.4. Lack of correlation between von Frey hairs and classic two-point discrimination. These data from Onne's work[3] demonstrate a wide range of two-point discrimination values possible for any given pressure threshold under 1.0 gm. For example, for a threshold of 0.3 gm in a fingertip following digital nerve repair, the Weber test result might range from 3 mm (S4 normal) to 18 mm (S3, only gross grip possible). (Reproduced with permission from L. Onne: *Acta Chir Scand [Suppl]* 300:5-9, 1962.[3])

Table 10.7
Correlation between Sensibility and Sensation[a]

Sensibility (Weber Test)	Sensation[b]			
	Poor	Fair	Good	Excellent
<10 mm	0	1	5	3
>10 mm	3	4	4	0

[a] Adapted from J. D. Schlenker et al.[21]
[b] Values indicate number of patients making objective assessment. Ability to move thumb, making moving-touch possible, was more critical to patient assessment than presence of a >10-mm Weber test result.

The moving two-point discrimination test was validated as a test of tactile gnosis by correlating its results with a test of hand function.[22] In this recent study patients with abnormal sensation following injury to the median nerve, but with normal thenar and ulnar motor function (Moberg's criteria[2], had a comprehensive evaluation of hand sensibility. This evaluation included moving and constant-touch, 30- and 256-cps vibratory stimuli, classic and moving two-point discrimination, vibratory, (Biothesiometer) and cutaneous pressure (Semmes-Weinstein monofilaments) thresholds, and a timed pick-up (sighted) and object recognition (blindfolded) test. The results demonstrated that tactile gnosis begin to recover when the moving two-point discrimination is less than 7 mm, a time during recovery from nerve re pair when classic two-point discrimination is usually greater than 15 mm (see Table 10.8).

This study[22] demonstrated for the first time the functional difference between a recovered peripheral innervation densities of the group A beta fiber subpopulations. Among the patients studied were those following nerve repair who had recovered to the point where they could perceive constant-touch, had wide ranging cutaneous pressure thresholds, and two-point discrimination greater than 15 mm. By Moberg's criteria, these patients should have no tactile gnosis I found that these patients could not perceive an object between their thumb and index finger if they held it with a static grip, nor could they identify the object using a static grip. They could perceive moving-touch had near normal vibratory two-point discrimination threshold at 120-cps, and moving two-point discrimination between 4 and 6 mm. I found that they could easily identify objects placed between their thumb and index finger if they moved the object between their fingers (Table 10.8). As moving two-point discrimination improved below 6 mm, the patient could identify objects more quickly and could identify smaller and more closely related objects. Certainly these patients without classic two-point discrimination had tactile gnosis.

Several patients in the study[22] permitted a fingertip biopsy in an area of carefully evaluated pulp (Fig. 10.5). For example, light and electron microscopy (Figs. 10.6 and 10.7) demonstrated absent Merkel cell-neurite complexes in an area, correlating with the absence of perception of constant-touch, unobtainable cutaneous pressure threshold and absent two-point discrimination. A pattern of reinnervated

Meissner corpuscles was present (Fig. 10.8), in an area with perception of 30-cps vibratory stimuli, an elevated vibratory threshold, and moving two-point discrimination of 10 mm. an innervated Pacinian corpuscle was present in this area, which correlated with the perception of the 256-cps vibratory stimulus.

Table 10.8
Correlation of Sensibility Testing with Hand Function*

Patient, Age	Pressure Threshold (Semmes-Weinstein Markings)			Vibratory Threshold (Vibrometer in microns)			Two-Point Discrimination (mm)				Tactile Gnosis	
							Classic		Moving		No. of Objects Recognized of 12	Mean Recognition Time per Object (sec)
	Control	Thumb	Index	Control	Thumb	Index	Thumb	Index	Thumb	Index		
Nerve repair												
L. F., 27	2.44	5.18	5.18	0.09	0.36	0.66	35	40	12	11	4	12.5
B. K., 22	3.84	4.31	4.56	0.09	0.09	0.09	13	25	7	10	6	4.5
K. L., 29	2.83	4.93	4.93	0.25	1.00	2.60	19	22	7	7	8	4.8
C. E., 24	2.83	4.74	4.93	0.09	0.36	0.66	50	50	10	10	8	7.5
O. O., 30	2.44	4.56	4.31	0.09	0.36	0.16	18	16	8	5	9	7.3
L. T., 30	3.84	5.88	6.10	0.16	0.36	0.50	40	40	8	6	11	17.0
E. L., 60	3.22	4.74	6.45	0.12	0.50	0.36	40	40	6	4	12	9.9
J. C., 34	3.84	4.93	5.18	0.25	1.00	1.00	40	40	4	4	12	9.8
C. H., 18	2.83	4.08	3.84	0.09	0.16	0.09	13	12	5	3	12	2.0
R. O., 23	3.61	3.61	3.84	0.09	0.09	0.66	9	12	2	4	12	5.7
J. M., 32	2.36	3.61	4.17	0.12	0.16	0.16	6	7	3	4	12	3.3
Nerve compression												
P. D., 37	3.61	5.46	5.46	0.25	0.66	0.66	40	40	10	8	10	9.9
D. C., 47	3.61	4.74	6.45	0.16	0.36	3.30	3	13	3	8	12	2.8
M. H., 47	2.83	3.84	3.84	0.25	0.66	0.66	4	7	3	3	12	2.6

* Adapted from A. L. Dellon and B. Munger.[22]

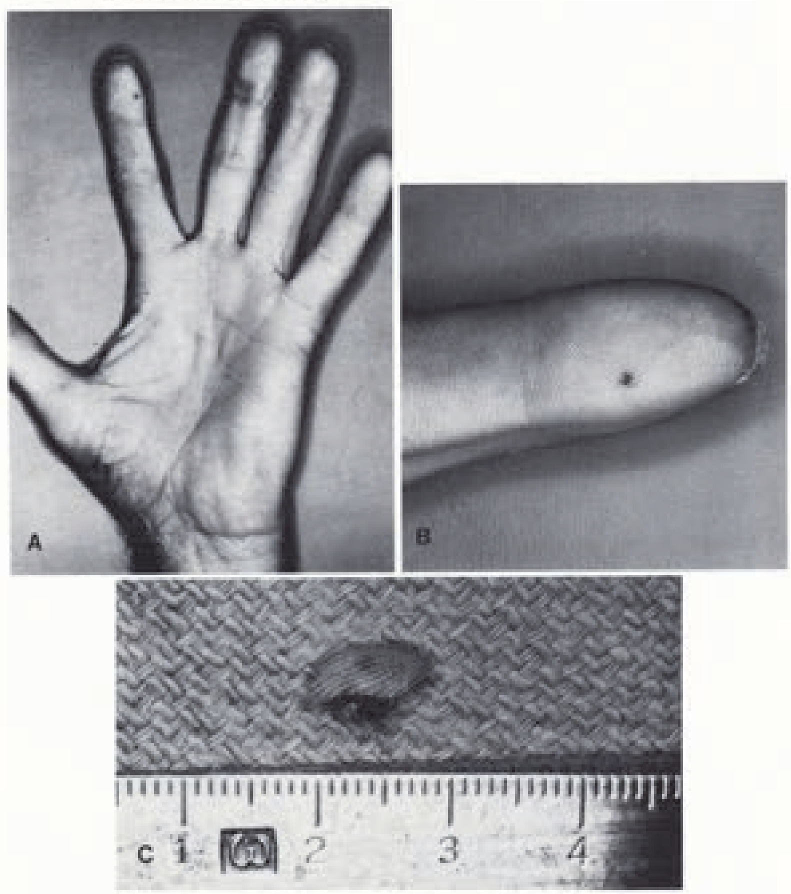


Figure 10.5. Correlation of sensibility tests, functional tests and histology. *A*, Hand of 62-year-old man 1 year after median nerve repair at wrist. *B*, Dot on index fingertip is center of area of high pressure threshold and absent two-point discrimination. *C*, Biopsy of this area in which vibratory threshold was near normal and moving two-point discrimination was present. (Reproduced with permission from A. L. Dellon and B. Munger, in press 1981.[22])

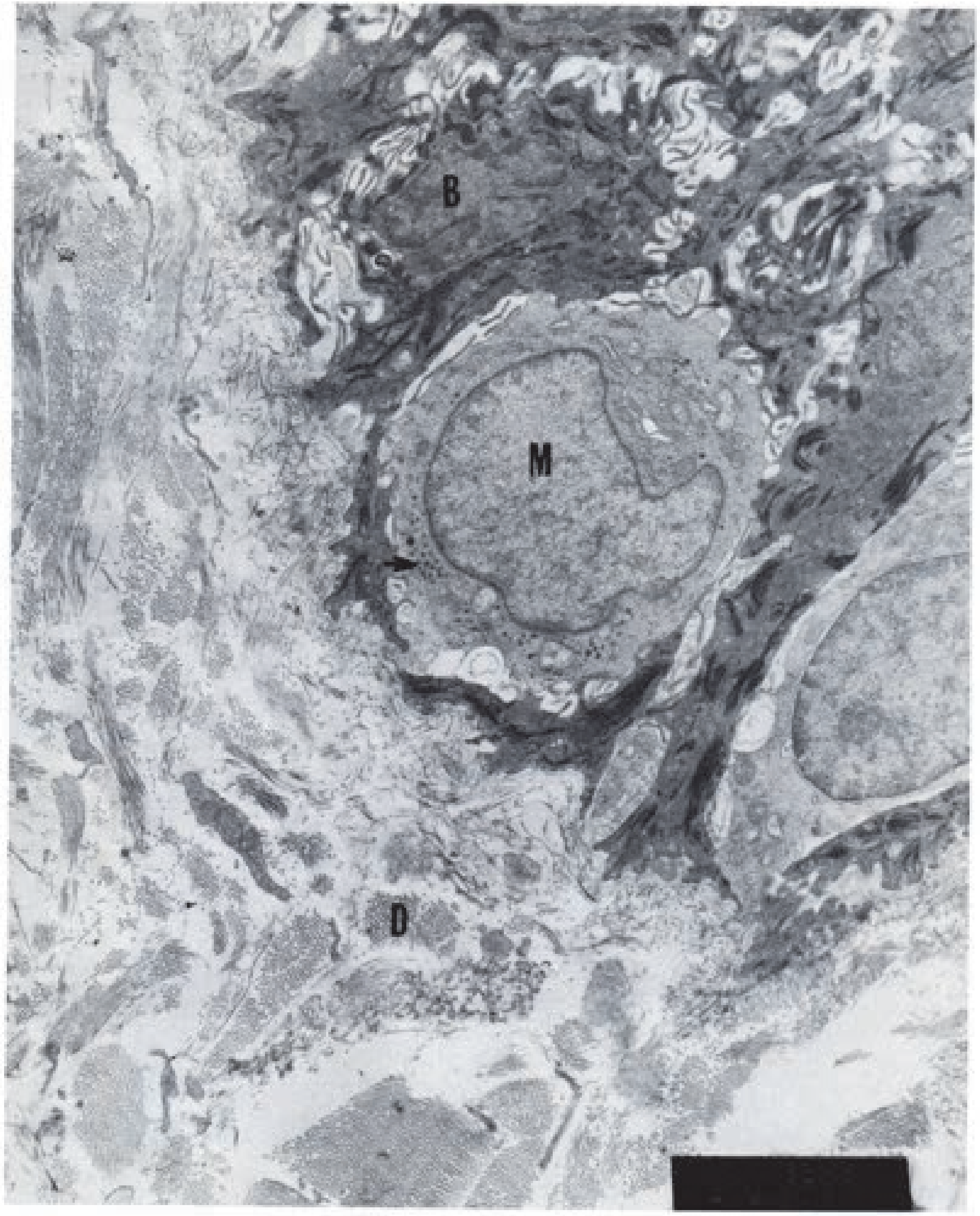


Figure 10.6. Correlation of sensibility tests, functional tests and histology. Electron micrograph (x4600) demonstrating a noninnervated Merkel cell from directly beneath blue dot seen in Fig. 10.5. Merkel cell identification by irregularity of nucleus (*M*) in cell at base of intermediate epidermal ridge with granular cytoplasm. Note absence of axon terminals around the Merkel cell. This was the only Merkel cell in the serial sections of the specimen except for that in Fig. 10.7. *D*, dermal papilla; B, nucleus of cell in basalar layer of epidermis. (Reproduced with permission from A. L. Dellon and B. Munger, in press 1981.[22])

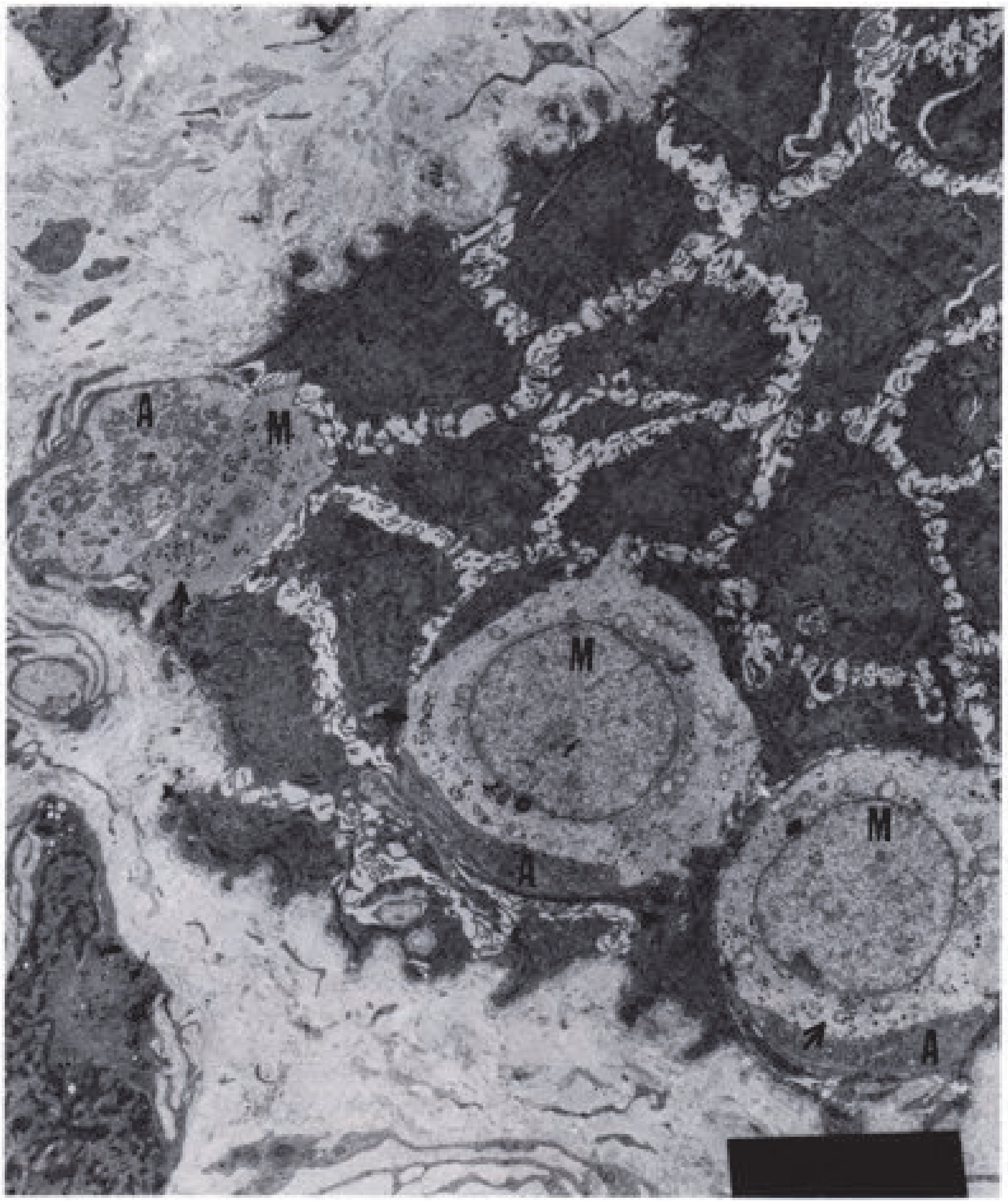


Figure 10.7. Correlation of sensibility tests, functional tests and histology. Electron micrograph (x2750) demonstrating an innervated Merkel cell (Merkel cell-neurite complex) from the most proximal end of the biopsy specimen in Fig. 10.4. These were the only other Merkel cells in the entire specimen. M, Merkel cell nucleus. Note axon terminals (*A*) forming "disc" below the Merkel cell and increased density of the granules in these innervated cells' cytoplasm. The presence of three Merkel cells in this one field is abnormal and represents a reinnervation pattern. (Reproduced with permission from A. L. Dellon and B. Munger, in press 1981.[22])

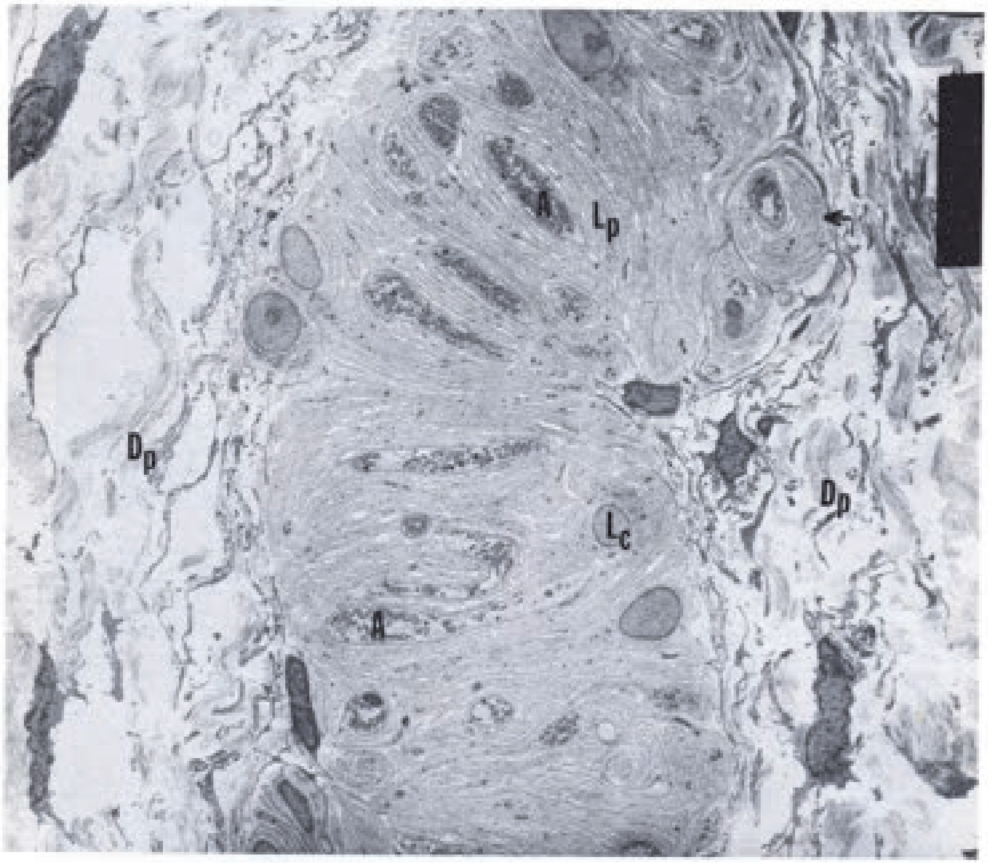


Figure 10.8. Correlation of sensibility tests, functional tests and histology. Electron micrograph (x1650) demonstrating an innervated Meissner corpuscle from the specimen in Fig. 10.4. Note lobulated appearance, multiple axon terminals (*A*) ensheathed by lamellar cell processes (Lp). Lamellar cell nuclei (Lc) are present at periphery of corpuscles were abundantly present throughout specimen. (Reproduced with permission from A. L. Dellon and B. Munger, in press 1981.[21])

Would electrodiagnostic techniques provide an alternative method or important adjunct to the evaluation of functional sensation? Should they be obtained routinely? It has been only relatively recently that sensory nerve conduction velocities have been measured by Dawson[23] in both antidromic and orthodiomic directions (1956). Melvin et al[24] have demonstrated that the sensory latency becomes prolonged sooner than motor latency in peripheral compression neuropathy. My preliminary data on correlating a comprehensive clinical evaluation with electrodiagnostic studies in the carpal tunnel syndrome[25] suggested that the tuning fork examination and moving two-point discrimination tests become abnormal earlier than the electrodiagnostic studies. These findings were supported by a later study including 80 extremities with nerve compression.[26] Bell noted that “when a loss of sensibility was measured by the monofilaments, so also was there a delayed or untestable sensory nerve conduction… However it is true that nerve conduction can sometimes show indications of a decreased latency before it can be measured by the monofilaments.” In 1970, Almquist and Eeg-Olofsson[27] reported nerve conduction-velocity in 19 patients who were at least 5 years median and/or ulnar nerve suture at the wrist.

There was no correlation between either conduction velocity or stimulus threshold and the degree of sensory recovery as evaluated by the classic two-point discrimination. (Fig. 10.9) Of potential interest is the recent work of Conomy et al.[25] with cutaneous electrical threshold testing. They are able to detect an abnormal threshold for detection of a 100-msec train of rectangular pulses at 20 Hz in children and adults. This, however, would seem to have little applicability to patients following nerve repair. I conclude that the results of electrodiagnostic studies now available do not correlate with functional sensation in the hand.

In summary, critical review demonstrates inadequacies in the correlation of tactile gnosis with classic two-point discrimination testing. These inadequacies are intrinsic to the test which measures the innervation density of only the slowly-adapting fiber/receptor system. These inadequacies are overcome by the moving two-point discrimination test. The results of moving two-point discrimination test correlate precisely with tactile gnosis throughout the period of recovery of sensation.

EVALUATION

The clinician attempting to evaluate hand sensibility must have at his disposal reliable and valid tests, a knowledge of the regional anatomy and the realization that his sensory examination must vary depending upon the clinical setting in the setting of acute trauma, the goal of the examination is to determine the integrity of the involved nerves. In the setting of nerve compression the goal of the examination usually is to determine the presence of early or subtle changes in sensibility. With more advanced cases of nerve compression, the goal is to determine the presence of intraneural fibrosis and, thereby, guide the therapeutic approach to include an internal neurolysis. In the setting of recovery following nerve repair the goal of the examination is first to determine if axonal regeneration is occurring at all. If regeneration is occurring, then the goal becomes to determine the sequence of recovery of sensory submodalities as a guide to instituting sensory re-education. Once sensory recovery has progressed, the goal of the examination changes again to determining the final status of sensibility in a way that reflects hand function the sensibility evaluation charts in Fig. 10.10 are helpful.

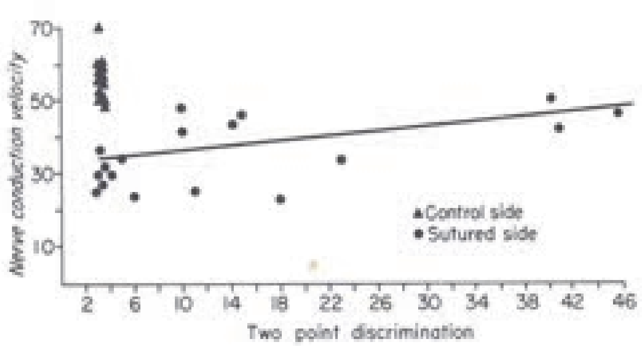
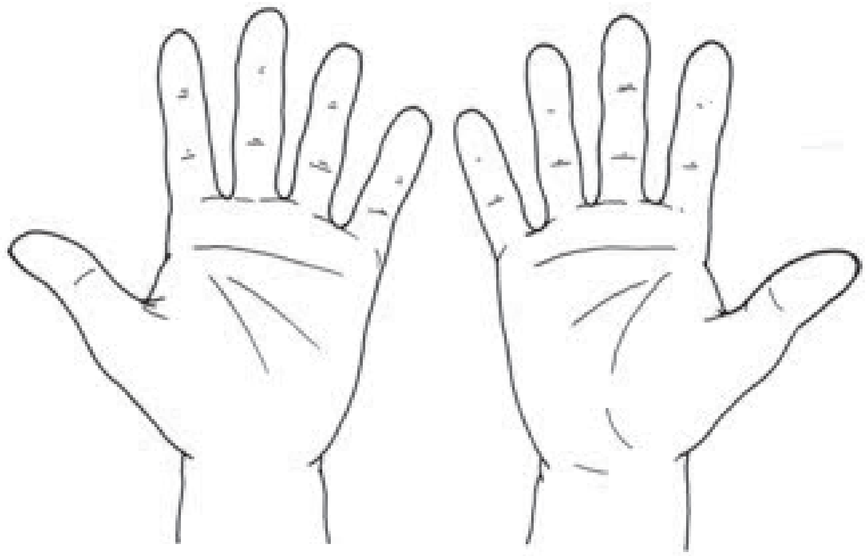


Figure 10.9. Correlation of electrodiagnostic studies with Weber test. There was no correlation between nerve conduction velocity and Weber test results in patients studied 5 years after nerve repair. If there had been a correlation, line would have sloped from upper left to lower right. (Reproduced with permission from E. Almquist and O. Eeg-Olofsson: *J Bone Joint Surg* 52A:791-796, 1970.[27])

Patient's name : ____________________

Examination date: ____________________



Left		Right
	Tinel's Wrist	
	Elbow	
	Phalen's	
	Extrinsics FDP_L	
	FPL	
	Intrinsics AbP	
	OpP	
	AbDM	
	IDI	

Ulnar vs. radial dorsal sensation

Left				Right		
Th	In	Li	sensory	Th	In	Li
			30 cps			
			256 cps			
			2PD			
			m2PD			
			misc.			

*	Tinel's
·······	30 cps
ooooo	256 cps
~~	Moving touch
——	Constant touch

Figure 10.10. Chart I use to record sensibility evaluation.

Trauma

When evaluating the acute injury, the nerves at risk for potential crush or division are suggested immediately by the location of the injury. Knowledge of the regional anatomy should guide the examination to the thumb, index, middle, and ring fingers for potential median nerve injury at the wrist, the little finger for a potential injury to the ulnar nerve at the wrist, and to the radial dorsal or ulnar dorsal aspects of the hand if injury may have occurred to the dorsal sensory branch of the radial or ulnar nerves, respectively. With an injury in the palm, the common volar digital nerves are, of course at risk, and the adjacent volar surfaces of the fingers on both sides of the web space must be examined. More distal injuries of course, may involve just a single digital nerve.

The examiner must be suspicious of puncture wound these are especially common in the palm and more often than not cause injury to the common volar digital nerves, usually the one to the ring/little finger web space.

The examiner must be suspicious of partial nerve division. These are most likely to occur to the median nerve at the wrist. Because of the ulnar nerve overlap in the ring and sometimes the middle finger, these injuries may be initially unnoticed by both patient and examiner.

In the acute setting in the emergency room, with the patient apprehensive and in pain, the environment loud and threatening, and the hand bandaged and often bleeding, the circumstances are clearly not ideal for comprehensive evaluation of sensibility. Furthermore, the patient is likely to be uncooperative, often being a child or an intoxicated adult. The diagnostic test must be one that is readily available, quick, reliable, valid and non threatening. My choice is the tuning fork.[25] I never use a needle. The tuning fork is demonstrated to the patient on his noninjured hand. Usually the examiner is not the first person to see the patient, and in that case if the fingertips are exposed, the bandage is not removed again, the use of the tuning fork is discussed in detail in Chapter 9, in brief, the prong end of the tuning form (usually a 256-cps tuning fork is available, but any one can be used in this situation) is touched to each finger and the patient asked if he can perceive the stimulus. If he says yes, he is then asked where he felt it, to be sure he is localizing it to the fingertip and not to the palm or proximal dorsal finger skin. He is then tested in this area again and asked if that stimulus feels the same as the stimulus applied to an adjacent finger, the contralateral finger, or the other digital nerve autonomous zone on the same finger, depending upon which nerve the examiner thinks is at risk for injury.

A diminished vibratory perception means there is loss of neural conduction in the nerve tested, and this loss is almost always due to nerve division. Occasionally, it has been found associated with a traction injury or a nerve contusion.[25] With careful testing, that is, being sure that the patient's perception is not from a more proximal level or from an uninjured adjacent nerve territory. I have not yet had a false negative or false positive with this test.

With a puncture wound or missile injury, if a diminished vibratory perception is present the possibility of a reversible nerve lesion, a neuropraxia, exists. If the wound would not otherwise require exploration, I suggest the patient be observed and serial sensory evaluations conducted. If by 4 to 6 weeks the vibratory perception remains abnormal, and local wound conditions permit, exploration is indicated.

In the acute situation, if time, the wound, and the patient permit, additional evaluations of sensibility can be carried out, either to “confirm” for the examiner or the patient the results of the tuning fork test or for the sake of “completeness” or “thoroughness.” I emphasize that the tuning fork exam in this setting I reliable and valid. What other sensory testing might meaningfully be done? For all the reasons discussed earlier in this chapter, the only other test that might prove useful, as a baseline or diagnostic study is the moving two-point discrimination test.[25] This is performed exactly like the classic two-point discrimination test (see Chapter 8) except that the two prongs are moved only in a longitudinal direction, from proximal to distal and at a perceptible pressure. Value of 4 mm or greater are abnormal and suggest nerve compression, single digital nerve injury or partial division of a more proximal major nerve. Absent moving two-point discrimination in a fingertip indicates complete conduction block (usually nerve transection) proximal to the common volar digital nerve level.

NERVE COMPRESSION

The sensory examination of the patient with a potential nerve compression is usually performed under more ideal circumstances than the examination on the trauma patient. The patient’s history and his complaints are most frequently sufficient to make the diagnosis of a peripheral nerve compression and often to suggest which nerve is compressed. However, to localize the level or the site of the compression, and the degree or the presence of intraneural fibrosis, evaluation of sensibility is a must.

The two indispensible tests are the tuning fork test[25] and the moving two-point discrimination test.[15] The only clinical tests of median nerve compression at the wrist to be evident earlier than abnormal vibratory perception in the thumb, are the provocative tests such as Phalen’s and Tinel’s sign.[25, 26] We have found abnormal vibratory perception in the presence of a normal Phalen’s and Tinel’s sign, and sometimes, in the rheumatoid, or after wrist fractures Phalen’s sign is not possible to test.

In the early nerve compression, a hyperesthesia occurs and the patient may perceive the tuning fork to be more, not less, intense.

Abnormal vibratory perception means the presence of a peripheral nerve conductions block but does not indicate the degree or severity of the block. This is assessed with the moving two-point discrimination test.[15] A value of 4 mm or more is abnormal and correlates with intraneural fibrosis.[29] The patient’s history at this point usually is positive for a persistent sensory disturbance, and I suggest that nerve decompression should be accompanied by internal neurolysis to give the best chance of complete recovery of sensation.[29]

With sensory disturbance related to the thumb, index, and middle finger, and abnormal vibratory perception in the thumb and index in contrast to the little finger or contralateral fingers, the diagnosis of median nerve entrapment is made. Weakness of the abductor pollicis brevis or opponens pollicis may be present (rarely) ahead of sensory change. Muscle wasting without diminished tactile discrimination is also an indication for internal neurolysis.[30]

With sensory disturbance related to the ring and little fingers, and abnormal vibratory perception in the little finger in contrast to the thumb and contralateral finger, the diagnosis of ulnar nerve compression is secure. However, at which level? Motor evaluation of the ulnar innervated intrinsics will confirm an ulnar nerve compression, but will not resolve the question, “At which level is compression occurring, wrist or elbow?” I have found the sensory examination of the dorsum of the hand to be critical. Often there will still be strength in the flexor profundus to the little finger, especially if the ulnar nerve compression at the elbow is in the dominant upper extremity. Almost invariably there will be diminished vibratory perception over the dorsal ulnar skin surface, in contrast to the ipsilateral dorsal radial and contralateral dorsal ulnar skin surface with ulnar nerve compression at the elbow. This indicates entrapment above the wrist. This, perhaps neurologically “soft sign” can be confirmed by gently stroking the dorsal skin with the examiner’s finger longitudinally, and moving these strokes successively from the radial to the ulnar half. Ask the patient to tell you when the sensation begins to change, or if it begins to change in quality.

A positive Tinel’s sign at the elbow over the cubital tunnel or just proximal to it is common throughout the population, especially if the person spends much time on the phone or working at a desk (elbows flexed). Thus, this sign, unless “four plus” is more confirmatory than pathognomonic. I have found, however, a positive Tinel’s sign just distal along the course of the ulnar nerve at the point where it goes between the two heads of the flexor capri ulnaris is highly diagnostic of ulnar nerve compression by Osborne’s band.[31] In the clinical setting of ulnar nerve entrapment with abnormal dorsal sensory examination, a tender area distal to the cubital tunnel has correlated invariably in my experience, with the presence of a fibrous band at this point.

Nerve compression is commonly a bilateral problem, and both median and ulnar nerve compression can occur in the same extremity. In these cases, tuning fork evaluation may not appear to be altered because the comparison area also has abnormal innervation.[26] For this reason, a quantitative test of sensibility is of value in all cases of suspected peripheral nerve compression I favor the moving two-point discrimination test.[15] Although the classic two-point discrimination test becomes abnormal with advanced nerve compression, the relatively wider range of normal usually given, i.e., 2 to 6mm, makes the test inherently less sensitive than the moving two-point discrimination test. For example, if perception of the tuning fork were equal in the thumb, index, and little finger, the classic two-point discrimination was 6 mm in each of these fingers and the moving two-point discrimination was 4 mm in each of these fingers, I would suspect compression of both the median and ulnar nerve in that extremity and proceed to very carefully compare both extremities again. I have operated upon four patients so far with bilateral nerve compression of the median, at the wrist, and ulnar, at the elbow. In these difficult bilateral cases, a quantitative measurement of vibratory threshold (vibrometer)[22] or cutaneous pressure threshold (Semmes-Weinstein monofilaments) can be helpful, but remember that these “absolute” values vary, for example, with age.

Nerve Repair

The sensory examination of a patient following nerve repair must be considered as a series of observations along the time continuum of recovery if we accept the average rate of regeneration of a peripheral nerve in the distal end of the extremity to be 1 mm per day, or 1 inch per month (see Chapter 7) then it should take about 6 months after nerve repair for the regenerating axons to reach the fingertip following suture at wrist level.

During the first 2 to 4 months following suture axon sprouts of all sensory submodalities are regenerating and are entering the palm. Most axons are destined for the fingertips and will not reinnervate the palm the axon sprouts from the smaller diameter fiber are in advance of the larger diameter fibers. At this stage, the evaluation of sensibility can be limited simply to following the Tinel’ sign progressing distally.[33,34] As reinnervation occurs, there will be the development of a state of “hypersensitivity,” “dysethesia” or “paresthesia.” Recovery of moving- and constant-touch and the perception of vibratory stimuli occurs next and these are often poorly localized. The goal of the evaluation at this point is to establish within 4 months whether regeneration is proceeding satisfactorily, which is to say at a pace commensurate with the patient’s age, the type of injury and its repair, skill of the surgeon, etc. If regeneration is not proceeding as expected, then, as discussed in Chapter 4, surgical intervention is justified before the sensory corpuscle population suffers irreversible degenerative changes. For “satisfactory regeneration”, I require: (1) an advancing Tinel’s sign and (2) the orderly distal progression across the palm of the expected pattern of sensory recovery (see Chapter 7). During this period it is useless and a waste of time to measure two-point discrimination or thresholds, as it is simply too early for them to have recovered in the palm and impossible for them to be present in the fingertips. The qualitative tests give the desired information.

From 4 to 6 months following nerve suture at the writ, the axon sprouts are entering the fingers. The goal of sensibility evaluation now is to guide rehabilitation. Moving-touch, constant-touch, 30- and 256-cpsvibratory stimuli are used exclusively until all have been recovered to the fingertips. Because of variability in peripheral nerve innervation patterns, the middle and ring finger are not tested nor are the dorsal aspects of the fingers. (The thumb, however, is carefully assessed during this time to ascertain the degree, if any, of anomalous radial nerve innervation of the thumb pulp.) Once each of these four sensory tests can be perceived at the fingertip it is not repeated at subsequent examinations.

Moving two-point discrimination is not tested until moving-touch is perceived at the fingertip. Moving-touch is then no longer individually tested. The tuning forks serve both as the earliest tests of recovery of the touch submodality and as an important guide to the institution of sensory re-education. However, one perception of moving-touch has recovered in the fingertip, the only test required thereafter in the routing evaluation of sensibility is the moving two-point discrimination test.[15]

The vibratory threshold is not evaluated routinely.[32] It may be of value in checking occasionally, as its progressive return towards normal can be recorded and demonstrated to the patient as a means of reassurance, helping him to endure the first postoperative year. The cutaneous pressure threshold (Semmes-Weinstein, von Frey) is not evaluated at all. I evaluated cutaneous pressure thresholds in the comprehensive study correlating sensibility tests with function and found these not to correlate.[22] There is a progressive change in cutaneous pressure threshold over time, but as this change can be shown with the vibrometer[32] and the vibrometer is quicker and easier to use (no log conversion scale or calibration problem) I prefer in those rare causes where it is needed, the vibrometer (see Chapter 9). Furthermore, by its very nature, the cutaneous pressure threshold must be done for multiple spots on a fingertip, using the series of different filaments at each spot. The vibrometer, since it employs a traveling wave as its stimulus, is more efficient. It can be tested on just one “spot,” the fingertip, giving an “average threshold” for the whole area. The patient, after all, feels with the fingertip not a small spot somewhere on its tip.

The classic two-point discrimination is not tested until perception of constant-touch has been recovered at the fingertip. At present, I am still recoding both the moving and classic two-point discrimination in each patient. Theoretically, this is not necessary it has been shown that the curve of classic two-point discrimination recovery over time parallels that for moving two-point discrimination, but is, in every instance, slower to recover (delayed, on the average, 6 months) ad is in every instance, a higher value (demonstrating a poorer degree of recovery, a poorer result).[15] I continue to record it for three reasons (1) At present, it remains the standard of comparison throughout the world; (2) it serves as a link between today’s evaluation and those classic studies of the past; and, (3) although the moving two-point discrimination test does test the slowly-adapting fiber/receptor population, in addition to its measurement of the quickly-adapting fiber/receptor population, the classic two-point discrimination test permits a separate quantitation of the system that mediates perception of constant-touch and pressure. This later information is worth knowing functionally and is discussed below.

End Results of Nerve Repair

The goal of evaluating the end results of a nerve repair is to determine the functional capacity of the hand. What type of work is the hand capable of performing? What is the permanent partial impairment? How does the technique of nerve repair or sensory re-education compare with some other techniques? How good a job did the surgeon do? What can the patient expect?

The first question is not “how should the evaluation be done? But, “when should the evaluation be done?” much of the past lack of understanding of sensory recovery came from the view that “sensory recovery continues throughout the fifth postoperative year.” A sense of frustration and complacency permeated the field. Once the repair was done, there seemed to be little to do except sit back, check the patient at yearly intervals, reassure them, and after 5 years record their “final check.” Of course, somewhere between 6 months and 1 year postinjury, or whenever motor function seems to return, or whenever the workmen’s compensation insurance carrier or the lawyer needed disability rating, a detailed sensory examination could always be done!

A program of sensory re-education (see Chapter 12) must be an integral part of the care of every patient with a nerve injury if the patient I to maximize the full sensory potential given to him by the nerve repair in the shortest possible time. Clearly then, frequent and early evaluation of sensibility must be done both by the therapist and the surgeon. If the evaluation of sensibility program outlined immediately above is employed, these evaluation sessions are brief because only those tests appropriate for the given degree of neurophysiologic recovery are used. An entire “battery” of sensibility testing is not ritually repeated every time the patient is seen sensory testing does not become a half hour chore.

At 1 year following repair of the median nerve at the wrist, even in the adult, an excellent approximation to the traditional 5-year result can be found if the patient has been in a program of sensory re-education. By 1 year, virtually all nerve fibers that are ever going to regenerate to the fingertips have done so. Threshold values, which reflect fiber/receptor maturation (the trophic influence of the regenerated corpuscular component) will continue to improve beyond 1 year. Tactile gnosis, which reflects the totality of axonal regeneration, maturation, and re-education will continue to improve beyond 1 year, and require continuing education or practice to be maintained. We have seen this 1 year mark delayed by intercurrent problems, such as pregnancy, where peripheral edema clearly slowed the recovery process. But, as a general statement, a good approximation of the 5-year end result and an accurate prognosis can be made at 1 year following nerve repair I n a patient receiving post-operative sensory rehabilitation.

Given only one test instrument to carry out the evaluation of sensibility in this end result type of examination, the paper clip should be chosen. Given only one test to carry out the evaluation of sensibility in this end result type of examination the moving two-point discrimination test should be done. Only the moving two-point discrimination test correlates with the hand function defined as tactile gnosis when the fingertips are allowed to move.[22] Movement is the way of life. The questing, working, active hand is most always a moving hand. The proof of this is that thumb, index and middle finger, with no “measurable useful” classic two-point discrimination (greater than 15 to 20 mm) can readily identify objects placed within their grasp by manipulating these objects.[22]

The classic two-point discrimination tests underestimates hand function greatly. It lags behind recovery of useful moving two-point discrimination by 6 months usually never recover to the same level as moving two-point discrimination, and accurately reflects only those hand functions for which a static precision sensory grip is employed. However, it provides one critical piece of information required for the comprehensive evaluation of sensibility. In the blindfolded patient, the hand with 5 mm of moving two-point discrimination can identify small objects placed within his grasp, but when the fingers stop moving, they become unaware that the objects are still within their grasp. The afferent information required to know how tightly to hold the object is not sufficient. Classic two-point discrimination testing is still recommended, therefore, to provide this information.

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