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

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A Lee Dellon, M.D.
Professor of Plastic Surgery
Johns Hopkins University

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.

A Lee Dellon, MD, PhD
Professor of Plastic Surgery
Professor of Neurosurgery
Johns Hopkins University
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 3

Re-Education of Sensation

Chapter 11
RESULTS OF NERVE REPAIR IN THE HAND

MEDIAN NERVE
ULNAR NERVE
DIGITAL NERVE
CONCLUSIONS

The proliferation of published symposia and monographs on upper extremity peripheral nerve problems in the last decade[1-13] attests to the continued general interest, numerous basic investigations, clinical work and FRUSTRATION in this field. Following World War II, debate turned (although unresolved) from the superiority of primary versus secondary nerve repair to three brightly flowing areas on the horizon, microsurgery,[14-16] nerve repair techniques,[17-27] and nerve grafting[28-34] The hand surgeon today, with superior training, technical skill, instrumentation, and a versatile eclectic approach to the injured nerve, nevertheless, still is reporting end results of nerve repair that cannot be shown statistically to be superior to those reported 2 decades ago.

The purpose of this chapter is to tabulate the past results of nerve repair to serve as an historic baseline for future comparison. We feel that part of the failure of recent reports to document the desired improved end result following the recent technical advances in nerve repair is less a failure of the technique than a failure of our ability to quantitate those end results. Furthermore, we feel that the observed failure to improve end results is less a failure of the technique than a failure of the patient to achieve the full potential inherent in the nerve repair. The first "failure" can be overcome, we suggest, by an improved measurement of end results of sensory recovery, the moving two-point discrimination test (see Chapter 8)[35] The second "failure" can be overcome we suggest, with a regular program of sensory re-education, instituted at the appropriate time in the recovery process see Chapter 12).

The studies included in this chapter are all those published since the end of World War II that contain sufficient information to permit their inclusion as baseline data. Because the majority of these studies have reported their end results according to the modification by Zachary and Holmes[36] of Highet's scheme, we have also presented the results in that format (see Tables 11.1 and 11.2). This scheme does not define a "good" or "bad" result, but rather permits the author to consider, for example, "useful median nerve recovers as M3 and S2+, useful ulnar nerve recovery as M2+ and S2+."[29]

Table 11.1
Classification of Sensory Recovery

Grade	Recovery of Sensibility
S0	No recovery of sensibility in the autonomous zone of the nerve
S1	Recovery of deep cutaneous pain sensibility with the autonomous zone of the nerve
S1+	Recovery of superficial pain sensibility
S2	Recovery of superficial pain and some touch sensibility
S2+	As in S2, but with over-response
S3	Recovery of pain and touch sensibility with disappearance of over-response[a]
S3+	As in S3, but localization of the stimulus is good and there is imperfect recovery of two-point discrimination[a]
S4	Complete recovery[a]

[a] These classifications were modified to include classical two-point discrimination ranges as follows: S3 has 2PD greater than 15 mm, S3+ includes 7- to 15-mm range, S4 includes 2- to 6-mm range.

Table 11.2
Classification of Motor Recovery

Grade	Motor Recovery
M0	No contraction
M1	Return of perceptible contraction in the proximal muscles
M2	Return of perceptible contraction in both proximal and distal muscles
M3	Return of function in both proximal and distal muscles to such a degree that all important muscles are sufficiently powerful to act against gravity
M4	All muscles act against strong resistance and some independent movements are possible
M5	Full recovery in all muscles

The diversity of criteria for judging end results by this scheme may be seen from the following, Nicholson and Seddon[43] regarded useful recovery as M4, S3+. Some authors have a different criteria depending upon which nerve is being discussed. For example, McEwan[46] regarded "useful" ulnar nerve as M2+, and "useful" median nerve as M3. For the median nerve, Sakellarides[47] regarded "good" as M3, S2+ and S3, and "excellent" as M4, S3+. For the ulnar nerve, Sakellarides[47] regarded "good" as M2+ and M3, S2+ and S3, and "excellent" as M4, S3+. Most recent use of the scheme[53] considered "good" for both median and ulnar nerves to be M3, S2+ and "excellent" to be M4, S3+. It is thus evident that "normal", M5, S4 is a level to be approximated, a level rarely, if ever, reached. As discussed fully in Chapter 10, "useful" recovery must be considered functional recovery, and functional recovery must be measured in terms of the presence of two-point discrimination. None of the studies included here were published after the description of the moving two-point discrimination test,[35] and so, this end result cannot be used for retrospective comparison in the tables to follow category S3+ includes patients with " some" recovery of two-point discrimination, while category S4 is "normal." Based on Moberg's work, [37 38] we assigned patients with two points discrimination of 7 to 15 mm to the S3+ group and those with less than 6 mm to the S4 group. Those with two point discrimination greater than 15 mm are in the S3 group, all the studies reported have been redefined in these terms and listed in the tables to follow (Tables 11.3 through 11.10)

Table 11.3
Results of Median Nerve Repair—Low

Reference, Date	Type of Trauma	Repair Timing	No. of Cases	Age	% Children	Follow-up (yr)	Motor Recovery (%)				Sensory Recovery (%)				
							M2	M3	M4	M5	S2	S2+	S3	S3+	S4
39, 1949	War	All	235	Adults	0	2	67				27		73		
40, 1954	War	Secondary	290	Adults	0	5	31	14	18	0	47	15	30	9	0.2
41, 42, 1956	War	Secondary	244	Adults	0	4	11	23	29	31	17	28	14	18	
43, 1957	Civilian	Secondary	52		16	5	21	27	39	0	21	15	40	25	0
44, 1958	Civilian	Primary	54		16	1–7	35	0	65	0	3	0	26	71	0
44, 1958	Civilian	Secondary	24		16	1–7	50	0	50	0					
45, 1961	Civilian	All	46			2–24									9
46, 1962	Civilian	All	27	<14	100	"Long"	0	0	27	65	4	0	4	7	86
46, 1962	Civilian	All	16	>14	0	"Long"	13	20	27	13	17	0	17	61	0
47, 1962	Civilian	Primary	38	3–81	26	2–31	13	37	11	0	15	33	13	5	0
47, 1962	Civilian	Secondary	20	3–81	26	2–31	25	35	25	0	20	29	32	4	0
48, 1962	Civilian	Primary	40			1–12	25	38	15	7	50	0	7	10	3
49, 1962	Civilian	Primary	15	<14	100	4–11	20	13	40	27	0	0	0	27	73
49, 1962	Civilian	Primary	17	>14	0	4–11	30	23	18	29	22	18	18	41	0
50, 1964	Civilian	All	10	5–58	33	1–3	30	70			30		70		
51, 1965	Civilian	All	26		35	1					0		88	8	4
2, 1972	Civilian	Secondary	110			5	5	47		44	4	5	47	44	0
52, 1974	War	Secondary	95[a]	Adults	0	1	61		39	0	61		39		0
53, 1980	Civilian	Primary	14		6	2–11	0	43	57	0	7	7	29	57	0

[a] Value includes ulnar nerve cases too.

Table 11.4
Results of Median Nerve Repair—High

Reference, Date	Type of Trauma	Repair Timing	No. of Cases	Age	% Children	Follow-up (yr)	Motor Recovery (%)				Sensory Recovery (%)				
							M2	M3	M4	M5	S2	S2+	S3	S3+	S4
39, 1949	War	All		Adult	0	<2					37		47		
40, 1954	War	Secondary	95	Adult		5	42	13	6	0	47	23	25	6	0
41, 42, 1956	War	Secondary	124	Adult	0	>4	17	25	30	13					
43, 1957	Civilian	Secondary	6	Adult		5	33	0	50	0	50	0	34	16	0
44, 1958	Civilian	Primary	14			1–7	0	14	36	0		8	50	42	0
47, 1962	Civilian	All	7	Adult		2–31	42	14	0	0	42	0	14	0	0
2, 1972	Civilian	Secondary	100			>5	6	61	30		3	6	61	30	
52, 1974	War	Secondary	48[a]	Adult	0	>1	7	3	27	0	7	3	27	0	0
53, 1980	Civilian	Primary	12	Adult	0	2–11	16	60	8	0	8	8	60	17	0

[a] Value includes ulnar nerve cases too.

Table 11.5
Results of Median Nerve Graft

Reference, Date	Type of Trauma	Gap Grafted	No. of Cases	Age	% Children	Follow-up (yr)	Motor Recovery (%)				Sensory Recovery (%)				
							M2	M3	M4	M5	S2	S2+	S3	S3+	S4
59, 1939	Civilian	3–15 cm	32[a]			1–15									3
60, 1947	War	5–15 cm	11	Adult		2–3	0	36	18	0	10	18	45	18	0
61, 1955	Civilian	>7 cm	33			>5	0	69	0	0	21	0	69	0	0
31, 32, 1976	Civilian	2–20 cm	38	8–62	3	5–11	7	21	14	46	3	0	60	34	3
63, 1977	Civilian	5–10 cm	8	17–38	0	1.5–2.5	12	0	50	0	13	0	12	63	12
64, 1978	Civilian	4–15 cm	6			1.5–2.5		33	16	33				33	
34, 1980	Civilian	>2 cm	8	15–57	0	1–5		0	0	0	0	37	38	25	0

[a] Value includes ulnar and digital nerves too.

Table 11.6
Results of Ulnar Nerve Repair—Low

Reference, Date	Type of Trauma	Repair Timing	No. of Cases	Age	% Children	Follow-up (yr)	Motor Recovery (%)				Sensory Recovery (%)				
							M2	M3	M4	M5	S2	S2+	S3	S3+	S4
39, 1949	War	All	158	Adults	0	<2					0	31	69	0	0
40, 1954	War	Secondary	384	Adults	0	>5	72	14	5	0	54	15	28	3	0
41, 42, 1956	War	Secondary	441	Adults	0	>4	5	34	38	16	16	24	19	13	0
43, 1957	Civilian	Secondary	60		16	>5	32	32	35	0	18	14	47	21	0
44, 1958	Civilian	All	62		16	1–7	63	0	37	0	4	0	33	63	0
45, 1961	Civilian	All	32			2–24									3
46, 1962	Civilian	All	23	<14	100	"Long"	4	25	67	4	0	0	5	23	72
46, 1962	Civilian	All	23	>14	0	"Long"	32	36	23	0	8	0	24	48	12
47, 1962	Civilian	Primary	39	3–81	26	2–31	30	6	0	0	25	15	23	5	0
47, 1962	Civilian	Secondary	29	3–81	26	2–31	20	7	3	0	30	13	27	13	0
48, 1962	Civilian	Primary	40			1–12	57	15	18	0	50	0	13	7	0
49, 1962	Civilian	Primary	10	<14	100	5–10	8	30	30	32	0	0	10	30	60
49, 1962	Civilian	Primary	7	>14	0	5–10					0	0	57	43	0
50, 1964	Civilian	All	16	5–58	33	1–3	30	70			38		62		
51, 1965	Civilian	All	19		35	1					4		76	20	0
2, 1972	Civilian	Secondary	119			>5	10	43		45	2	10	43	45	0
52, 1974	War	Secondary	95*	Adults	0	>1	61		39	0	61		39		0
53, 1980	Civilian	Primary	20		6	2–11	55	30	10	0	50	0	10	30	0

* Value includes median nerve cases too.

Table 11.7
Results of Ulnar Nerve Repair—High

Reference, Date	Type of Trauma	Repair Timing	No. of Cases	Age	% Children	Follow-up (yr)	Motor Recovery (%)				Sensory Recovery (%)				
							M2	M3	M4	M5	S2	S2+	S3	S3+	S4
40, 1954	War	Secondary	105	Adult		5	23	5	1	0	53	24	23	0	0
41, 1956	War	Secondary	240	Adult	0	>4	9	38	32	10					
43, 1957	Civilian	Secondary	9	Adult		3	33	22	22	0	33	11	44	11	0
44, 1958	Civilian	Primary	18			1–7	0	0	0	0	0	16	44	44	0
47, 1962	Civilian	All	18	Adult		2–31	56	11	0	0	40	22	11	0	0
2, 1972	Civilian	Secondary	140			>5	13	61		22	4	13	61	22	0
52, 1974	War	Secondary	48*	Adult	0	>1	73		27	0	73		27	0	0
53, 1980	Civilian	Primary	11	Adult	0	2–11	54	18	9	0	27	9	27	0	0

* Value includes median nerve cases too.

Table 11.8
Results of Ulnar Nerve Graft

Reference, Date	Type of Trauma	Gap Grafted	No. of Cases	Age	% Children	Follow-up (yr)	Motor Recovery (%)				Sensory Recovery (%)				
							M2	M3	M4	M5	S2	S2+	S3	S3+	S4
59, 1939	Civilian	3–15 cm	32*			1–15									0
31, 32, 1976	Civilian	2–20 cm	39	11–69	23	5–11	8	31	18	31	0	15	65	15	5
63, 1977	Civilian	2–6 cm	2	16–50		1.5–2.5	0	50	0	0	50	0	50	0	0
64, 1978	Civilian	3–7 cm	10			1.5–3.5	20	50	30	0	20	20	40	20	0
34, 1980	Civilian	>2 cm	5	15–57		1–5			20		0	0	60	0	40

* Value includes median and digital nerves too.

Table 11.9
Results of Digital Nerve Repair

Reference, Date	Type of Trauma	Repair Timing	No. of Cases	Age	% Children	Follow-up (yr)	Nerve Block	Sensory Recovery (%)				
								S2	S2+	S3	S3+	S4
54, 1927	Civilian	All	105				No					
44, 1958	Civilian	All	142		16	1–7	No	7	0	29	64	0
55, 1961	Civilian	Primary	12	7–55	8		No	0	0	16	42	25
55, 1961	Civilian	Secondary	12	7–48	8		No	0	16	16	21	63
49, 1962	Civilian	Primary	8	<14	100	4–15	Yes	0	0	0	0	100
49, 1962	Civilian	Primary	14	>14	0	4–15	Yes	28	0	29	43	0
56, 1970	Civilian	Primary	24	<19	100	2–6	Yes	12	0	20	20	48
56, 1970	Civilian	Primary	50	>19	0	2–6	Yes	28	0	28	28	16
57, 1972	Civilian	All	18	6–51	5		No	0	0	22	28	50
58, 1979	Civilian	Primary	62	6–67	22	5–15	Yes	0	10	16	55	19
53, 1980	Civilian	Primary	71		6	2–11	No	20	0	32	48	0

MEDIAN NERVE

Low Repair

In the war injuries, of the 864 patients reported, just one patient recovered to S4 and less than 20% to S3+. About 40% recovered to M4. These results were not better after Vietnam than after World War II.[52] In the civilian adult injuries treated with nerve repair, of the 465 patients reported, just two patients recovered S4 and 33% to S3+. Less than 5% recovered to M5 and 40% to M4 (within this M4 group, studies ranged from 11%[47] to 65%[44])Among these 158 patient who recovered good to excellent sensory function were probably the 48 children included in these studies, but it is impossible to separate them from these "adult" results. It is quite possible that no adults recovered to S4 and that just 24% recovered to S3+ when evaluated at an average of 5 years after their nerve repair (see Table 11.3)

High Repair

In the war injuries, 0% recovered S4, 3% recovered S3+, and 5% recovered M5, 20% recovered M4, and 17% recovered M3. In the civilian injuries, 0% recovered S4, 17% recovered to S3+, and 0% recovered M5, 30% recovered M4, and 44% recovered to M3. These reports included no children (see Table 11.4).

Nerve Graft

Taken as a whole, the nerve graft patients had 2% recover to S4, 24% to S3+ and 20% to M5, 13% to M4 (see Table 11.5).

ULNAR NERVE

Low Repair

In the war injuries, of the 1098 reported patients, none recovered to S4, and less than 15% to S3+ and 40% to M4. The results were not better after Vietnam than they were after World War II.[52] In the civilian adult injuries treated with nerve repair, of the 466 patients reported, just three patients recovered to S4 and 34% to S3+. Thirty-two percent recovered to M4 (within this M4 group, reports ranged from 3[47] to 67%[46]). Among the 146 patients who recovered good to excellent sensory function were probably the 49 children included in these studies, but it is impossible to separate them from these "adult" results. It is quite possible that no adults recovered to S4, and that just 20% recovered to S3+ when evaluated at an average of 5 years after their nerve repair (see Table 11.6)

High Repair

In the war injuries, 0% recovered to S4 or S3+, while 6% recovered to M5 and 23% to M4 In the civilian injuries, 0% recovered to S4, 20% to S3+ and 0%d to M5, 17% to M4 (see Table 11.7).

Nerve Graft

Taken as a whole, the nerve graft patients had 7% recovery to S4, 14% to S3+ and 23% to M5, 20% to M4 (see Table 11.8).

DIGITAL NERVE

Nerve Repair

In the civilian adult injuries treated with nerve repair, of the 381 patients reported, 11% recovered to S4d and 48% to S3+. Among these 221 patients who recovered good to excellent sensory function, were probably the 47 children included in these studies, but it is impossible to separate them from these "adult" results. In the two studies in which children were separated from adults,[48, 56] when the results are pooled and averaged, 60% of children and 12% of adult recovered to S4, while 16% of the children and 30% of the adults recovered to S3+ when evaluated at an average of 5 years after the repair (see Table 11.9);

Nerve Graft

Taken as a whole, the nerve graft patients had 9%d recover to S4 and 20% recover to S3+ (see Table 11.10).

CONCLUSION

Seddon began his chapter on "Results of Repair of Nerve"[2] without such a review of the literature on end results. He wrote, "Earlier series of results of nerve suture have been reported, but even to summarize them would be a fruitless exercise, largely because there have been no universally agreed criteria for assessment." As indicated in the introduction to this chapter the main purpose of this review is to serve as the "historic control" for the chapter to follow which will include the effect of a sensory re-education program on the results of nerve repair. But this chapter's review of 27 studies, precisely because it does highlight the deficiencies of previous end result reports, hopefully will be fruitful in providing a stimulus for the appropriate design of future studies.

What can be concluded from the studies reviewed? All who addressed the question of the effect of age on results of nerve repair agreed that children obtain better results than adults.[4] The few studies that subdivided their patient population into children (usually less than age 14 or 16) versus adults[4] demonstrated this conclusively for sensory recovery in distal, median and ulnar nerve[46, 49] and digital nerve repairs.[49,56] The results are not as clear with respect to motor recovery[49] (see Table 11.11). However, even with these studies, we can criticize their basic design. McEwan's study[46] included both primary and secondary repairs, while the study of Onne[49] has very small numbers. I feel, however, that it is probably the most valid conclusion of all to state that patients age at the time of nerve repair directly affects the degree of sensation recovered. Seddon's[2] data effectively demonstrates this (Table 11.12), and this was one of the basic conclusion of Onne's study of "ideal" nerve repairs.[49]

When the S4 and S3+ columns of Tables 11.3 through 11.10 examined for each paper with respect to the children included in each study and when each author's text is carefully examined, it appears that the vast majority of those patients reported to have achieved excellent sensory recover are children. This age-related effect is so critical to end results analysis that Moberg[4] suggests all future reports be tabulated so as to relate patient age and recovered (classical) two-point discrimination.

Table 11.11
Results Summary

	No. in Group	Degree of Recovery			
		M4 (%)	M5 (%)	S3+ (%)	S4 (%)
Median					
Low repair					
War injury	864	40	0	20	0.1
Civilian injury[a]	465	40	5	33	0.5
Children	42	31	51	14	83
High repair					
War injury	266	20	5	3	0
Civilian injury	139	30	0	17	0
Graft					
Civilian injury	104	13	20	24	2
Ulnar					
Low repair					
War injury	1098	40	0	15	0
Civilian injury[b]	466	32	0	34	0.7
Children	33	55	12	24	70
High repair					
War injury	393	23	6	0	0
Civilian injury	196	17	0	20	0
Graft					
Civilian injury	56	20	23	14	7
Digital					
Civilian injury[c]	381			48	11
Children	32			16	60
Graft	72			20	9
Total	4607				

[a] Group includes 48 children.
[b] Group includes 49 children.
[c] Group includes 47 children.

Table 11.12
Influence of Age on End Results of Nerve Repair[a]

Age Group	n	Good (M4, S3+)	Fair (M3, S3)	Poor (M2, S2)	Bad (M1, M0, S1, S0)
0–10	35	71	29		
11–15	47	58	32	4	6
16–20	106	33	46	9	12
21–30	231	25	59	9	8
31–40	109	30	46	16	8
41–50	32	31	50	19	
51	24	20	58	13	8
Total	584				

[a] Adapted from H. J. Seddon,[2] includes median and ulnar nerves, all levels of repair.

A second area about which all studies agree is the effect of the level of nerve repair, in terms of proximal (high) versus distal (low). For the median nerve (Table 11.3 versus 11.4) and the ulnar nerve (Table 11.6 versus 11.7), it is clear that the more distal the nerve repair, the better is the decree of both motor and sensory recovered (see Table 11.11). Even when the most distal nerve repairs are sub-divided (Table 11.13), the results of sensory recovery can be related to the level of repair.

Table 11.13
Effect of Level of Repair on Outcome of Digital Nerve Repair[a]

Level of Repair	Recovery of S3+ (%)
Proximal palm	25
Mid-palm	50
Metacarpal	50
Proximal interphalangeal joint	48
Distal interphalangeal joint	75

[a] Adapted from J. L. Posch and F. de la Cruz-Saddul.[53]

Most disturbing, perhaps, is that after 3 decade of analyzing results of nerve repairs, we are still unable to say with certainty whether primary versus secondary or nerve repair versus nerve graft gives the better results. Why haven't we been able to answer these questions? Studies haven't been designed correctly. For example, those that sub-divided their cases into primary versus secondary didn't further subdivide into children versus adult[44, 47, 55] and had very small groups of patients.[55] It is not appropriate to compare the reports of primary[48,49,53, 56-58] to those of secondary[2, 40, 43, 52] repair because left uncontrolled would be mechanism of injury (war versus civilian), surgical technique, and patient age. Of course those studies that lumped all nerve repairs together are useless in this regard.[39, 44-46, 50, 51] These same criticisms apply to the question of nerve repair versus nerve graft. A nerve graft procedure implies a secondary repair, and usually a mechanism of injury less favorable than that in the patient group for whom primary repair was possible. Thus, it is probably never correct from a statistician's point of view to compare these two groups of patients. However, given all these caveats, it is interesting to note that for civilian injuries, the best nerve graft results[31, 32] (Tables 11.5, 11.8) compare quite favorably (if not better) than the best primary nerve repair results[48, 49, 53] (Tables 11.3, 11.6) and even to the best secondary nerve repair results[2] (Tables 11.3, 11.6) in adults for both median and ulnar nerves (see also Table 11.11).

If the "odds" are stacked against the nerve graft, how can the results of Millesi[65] be comparable to or better than nerve repairs? Certainly his emphasis on a tension-free repair, meticulous preparations of the nerve stumps, microsurgical techniques, and inter-fascicular grafting are critical. Millesi's patient also, however, receive significant postoperative sensory rehabilitation the nerve grafting results being reported from the Saint Louis group[34] are also comparable to or better than the results of nerve repair (see Table 11.11). Although these patients did not uniformly go through a sensory re-education program,[66] they were in a hand center that is well aware of our approach of applying specific sensory exercises at the appropriate times in the recover process.[9] These patients must have received frequent postoperative sensory testing this postoperative attention, similar to that now devoted to the postoperative care of replant patients, I believe, places these patients into a separate category, a category that bridges the gulf between the nerve repair patient, who in the past has received little if any organized sensory rehabilitation and the nerve repair patient of today, who has available the benefits of a formal program of Sensory Re-education (see Chapter 12).

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Chapter 12
RE-EDUCATION OF SENSATION

ROOTS OF SENSORY RE-EDUCATION
TECHNIQUES OF SENSORY RE-EDUCATION
RESULTS OF SENSORY RE-EDUCATION AFTER NERVE REPAIR
OTHER APPLICATIONS OF SENSORY RE-EDUCATION

Without sensation, a worker can scarcely pick up a small object, and he constantly drops things from his grasp. The so-called eyes of his fingers are blind.

S. Bunnell, 1927[1]

My interest in evaluating sensibility grew from the experiences of the summer of 1968. During the preceding Spring quarter, as a sophomore medical student as Johns Hopkins, I had taken a research elective with Doctor John E. Hoopes in the Division of Plastic Surgery. We worked on cleft palate speech problems. There was a bimonthly Hand Surgery Conference, attended by both Doctor Milton T. Edgerton, Chief of the Division, and Doctor Raymond M. Curtis, Hand Consultant. The conferences were stimulating. That summer, while continuing work with lateral view, sound cineradiography to evaluate cleft palate speech, I received permission to observe Doctor Curtis in surgery at the Children's Hospital on Tuesdays. One day, after witnessing a meticulous nerve repair, I asked Doctor Curtis, "What are the results of nerve repair?" "Very few people recover normal sensation," he said.

The apparent gap between technical expertise in the operating room and functional recovery in the examining room was disturbing to me. In the hand, especially, structure and function were so intimately related, so clearly evident. Yet with a nerve, precise fascicular realignment seemingly failed to result in a correspondingly good functional result. In the Fall of 1968, during my clinical rotations. I began to review Doctor Vernon B. Mountcastle's neurophysiology course from my freshman year of medical school. The basic neurophysiologic concepts which had been revealed by his laboratory, and reviewed in his textbook[2] quite suddenly seemed immediately relevant to the clinical paradox of sensibility! As outlined earlier (see Chapter 3), the definitions of subpopulations of the group A beta fibers, based upon their tuning curves, could be translated clinically into a 30-cps and a 256-cps tuning fork examination. I obtained permission to study a group of patients recovering from nerve injury. This approach to evaluating sensibility in the hand was begun in the Department of Rehabilitation Medicine, where Janice Maynard, M.A.O.T., O.T.R. was in charge of Occupational Therapy.

During my junior year in medical school I continued to attend the Hand Conferences. When a patient recovering from a nerve injury was presented, I observed that after the patient would respond to pinprick, light fingertip stroking, and pressure, he was still unable when "blindfolded" to pick out correctly a nickel from a quarter held in the examiner's palm. Leaving the conference room with the patients, I would meet them in the hall and ask to examine their hand again. It seemed to me that the necessary sensory submodalities had recovered but, perhaps because of "incomplete recovery" or fiber misdirection, the patient was simply confused by what he was feeling. I would place the nickel in the patient's hand and then the quarter, asking him "Can you feel these?" The answer would be "Yes." Then with his eyes shut and after feeling each again, I would ask him, "Do they feel like a nickel and quarter used to feel?" The answer, "No." Clearly there was sufficient sensory information being perceived to permit a distinction by the patient between the two objects but the question "Is that a nickel?" was ambiguous. Upon reflection I realized it was really two questions. One, "Do you feel something in your hand?" and two, "What is it?" The patient was passing the object perception question but failing the object recognition questions. His sensibility had recovered but his attempted matching of the new, altered profile of impulses with past association cortex profiles always read "mismatch." Now, giving the nickel back, I'd say, "Shut your eyes. This is a nickel. It doesn't feel the way a nickel used to feel, but you much now call whatever you are feeling a nickel." The same was repeated with the quarter. Then, upon retesting, the patient could correctly, "blindfolded," choose the nickel or the quarter from my palm. Within a few minutes he had relearned the names of common objects, his sensation had been *re-educated.*

This approach to evaluating sensibility in the hand and the results of the first series of patients we re-educated were presented to the Johns Hopkins Medical Society in May of 1970, just prior to my graduation from medical school. This work was presented to the American Society for Surgery of the Hand at their 1971 meeting in San Francisco, during my internship. The abstract of that presentation was published in the *Journal of Bone and Joint Surgery* in 1971.[3] The full manuscript, rejected by the Journal, ultimately was published. It had to be divided into a part on evaluating recovery of sensation, which published in the *Johns Hopkins Medical Journal* in 1972,[4] and a part on re-education, published in *Plastic and Reconstructive Surgery* in 1974![5]

ROOTS OF SENSORY RE-EDUCATION

We see a little farther ahead because we are standing on the shoulders of those who came before.(6)

Sir Isaac Newton, 1675

As I reviewed the literature in preparing this monograph, it has become very clear that examples of sensory re-education have been documented previously, although they were unrecognized as such. One category of observations that may be explained on the basis of sensory re-education is the universal finding that sensory recovery continues to improve slowly for many years after nerve repair. Hakstian[7] calls this phenomenon "the drop-off to recovery toward completion of regeneration that characterizes all peripheral nerve sutures." An example of this phenomenon is supplied from the Nicholson and Seddon[8] data. In a group of ulnar nerve repairs, 5% of patients had achieved sensory grade of 3+ by 1 year following repair. By 3 years following the repair, this sensory grade had been achieved by 15% of the group and at 5 years 21% of the group. Moberg[9] also seems to favor a prolonged course of nerve regeneration as an explanation for this. His "working hypotheses" is that "the larger fibers for tactile gnosis regenerate slower than the small fibers for sudomotor functions. Two-point discrimination is not regained for five years." I believe this hypothesis is untenable in view of the known capacity of axons to regenerate at about 1 mm per day in the distal upper extremity[10-11] (see Chapter 3). Even at 1 mm per day (1 inch per month), in the average sized adult, with the distance from the wrist to the fingertips being about 6 inches, regenerating axons of the thinnest diameter should arrive no later than 6 months, and probably by 1 year all axons have regenerated to the fingertip. I suggest that the further continued improvement in sensation is in part due to maturation of the newly re-united fiber/receptor systems, but primarily to the subliminal re-education that attends the daily, though guarded, use of the injured hand.

Sensory re-education allows the patient to achieve the potential for functional recovery provided by the nerve repair. Implicit in this statement is the assumption of use of the injured hand, if not in the formal sensory re-education program, then in an intrinsically motivated setting. I believe Davis[12] reported essentially this in 1949. Davis was working with Sowden on the staff of the Medical Research Council in London and was a Lecturer in psychopathology at the University of Cambridge. He studied 82 patients who had been treated in the Peripheral Nerve Units during the war. He related their "relative academic and functional recovery" to their degree of disability, present and previous employment, and job satisfaction. He concluded that functional recovery was favored by exercise and that recovery was better where the tendency to use the limb was stronger and where use was begun earlier. More recent, but parallel, observations by Honner, Fragiadakis, and Lamb[13] support this general hypothesis. They found that "the best results (of nerve repair) were obtained in skilled or dexterous workers, compared with semi-skilled, or heavy manual labourers, clerical workers or housewives."

The ultimate capacity for tactile discrimination in the normal hand remains to be defined. Observations that may be interpreted as demonstrating sensory re-education in the noninjured hand are available in the control groups in Onne's series[14] and in my own series.[5] In establishing normal values for the two-point discrimination test, Onne tested a series of controls on two separate occasions. One patient's two-point discrimination decreased by 6 mm between trials. In our initial group of patients having sensory re-education we tested two-point discrimination in the normal hand at each testing session. In four patients, the initial value decreased from 6 to 6.5 mm, 4 to 2 mm, 3 to 2.5 mm, and 4 to 2 mm as the program progressed. This sensory re-education in the normal hand is emphasized by the capacity of formerly sighted (blind) individuals to read braille. Heinricks and Moorehouse[15] evaluated two-point discrimination in nondiabetis blind people. Whereas the normal value in their control group was 3 to 5 mm, the blind braille readers had a two-point discrimination of 1.5 mm. these findings have been supported by the independent study of Almquist.[16]

The results of nerve repair in children have been found consistently superior to those in adults (see also Chapter 11).[12,14,17] The usual "explanation" for these better results is a presumed superior ability of their central nervous system to compensate for misdirected axons. However, Bach-y-Rita's extensive experience in retraining blind people with the tactile visual substitution system,[18-19] and his experience with recovery from brain lesions, i.e., strokes,[20, 21] has demonstrated that the young adult and the senior citizen also possess a remarkable capacity for cerebral reorganization. "However, training has been found crucial in adaptation to the tactile visual substitution system, even as it is in obtaining functional recovery from experimental or clinical brain lesions. The cerebral reorganization revealed by such functional recovery may have features in common with the reorganization necessitated by processing information received through the skin in visual terms."[20] Retraining has been found to enable monkeys to recover precision tactile activities after parietal lobe lesions, too.[22] I wonder, therefore, if the success of children in recovering their functional sensations after nerve injury is not at least partially due to their continual curious investigation of their environment with their hands.

Another set of observations that may be interpreted to demonstrate sensory re-education is derived from the relationship between the Meissner corpuscle and moving-touch. In Chapters 3 and 10, the neurophysiologic basis for designating the Meissner corpuscle as the receptor for the low frequency quickly-adapting fiber/receptor system, and the function of the system in mediating the perception of moving-touch was outlined. It has been demonstrated that the absolute number of Meissner corpuscle diminished with age (Fig.12.1).[23] It would seem natural therefore if Meissner corpuscle function diminished with age, that when a specific test of this sensibility, such as receptor threshold, is studied by means of vibration of varying amplitude, an age-related effect is found. Vibratory thresholds, indeed, do increase with increasing age (Fig 12.2).[24] However, the normal values for the moving two-point discrimination test show little change with increasing age (Fig 12.3).[25] Moving two-point discrimination is a test of the innervation density of the quickly-adapting fiber/receptor systems and might be expected to show, therefore, more variation with age. However, his test requires conscious discrimination of tactile patterns. I suggest that the component of central learning can be invoked to "override" a physiologic peripheral loss, and thus there is little change in moving two-point discrimination with age. I suggest that if the fingers are kept active, then despite advancing chronologic age, the biologic capacity for tactile discrimination will not be diminished. Constant activity is the sensory re-education that provides a physiologic face-lift to the wrinkled hand.

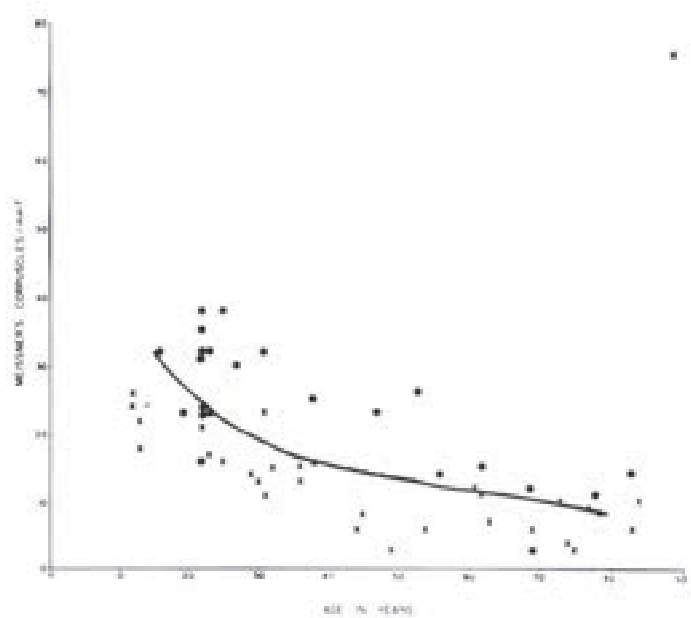

Figure 12.1. Diminution of Meissner corpuscle concentration with increasing age in the fingertip of man. (Reproduced with permission from C. F. Bolton et al,: *Neurology* 16:1-9, 1966[23])

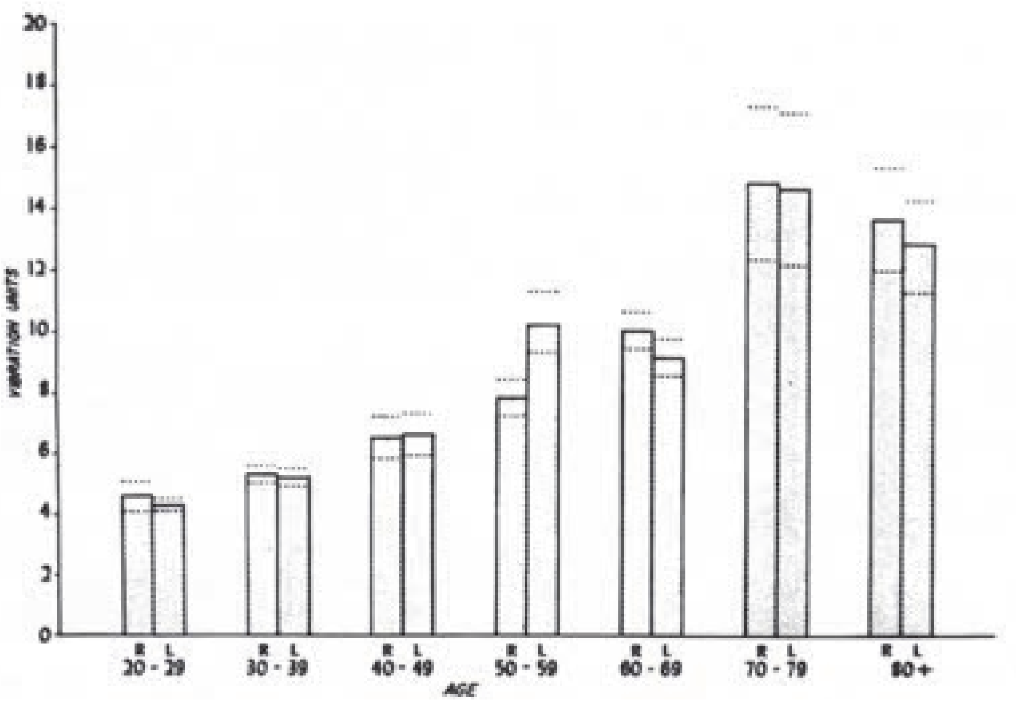

Figure 12.2. Increase in vibratory perception threshold for a 125-cps stimulus with increasing age. (Reproduced with permission from G. Rosenberg: *J Am Geriatr Soc* 6:471-481, 1958[24]

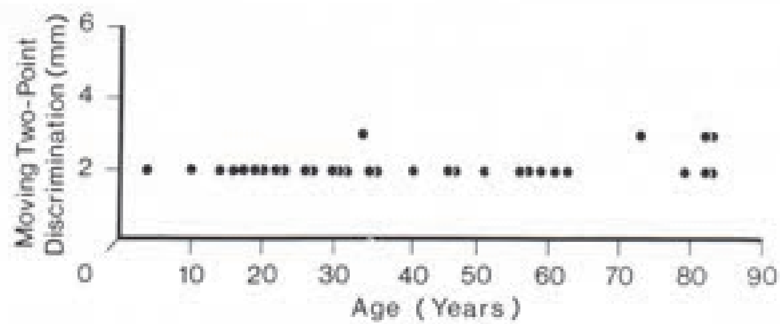

Figure 12.3. Normal value of the moving two-point discrimination test, demonstrating little, if any, increase in the limen with increasing age. (Reproduced with permission from A.L. Dellon: *J Hand Surg* 3:474-481, 1978[25])

Another example that demonstrates re-education is that a transplant assumes the sensory characteristics of its recipient site. In the classic study of Hutchinson, Tough, and Wynburn.[26] From 1949, classic two-point discrimination was measured in human abdominal skin grafted to the face or fingertips. The two-point discrimination of the normal abdominal skin was 20 to 25 mm. when tested 2 to 18 years later, there were examples of recovered two-point discrimination of 4 mm on the face and 6 mm on the fingertip. Sturman and Duran[27] reported similar results, including donar sites of forearm skin, dorsal, palmar, and abdominal flaps.

Transferring toe pulp to the fingertip offers another demonstration of sensory re-education having occurred. The plantar tissue has been found to have an average classic two-point discrimination of 11.3mm for the great toe (range, 7 to 18 mm), and an average of 16.4 mm for the second toe (10 to 25 mm) (28) In 1974, Maquieric reported transferring a plantar nerve innervated pulp graft to the fingertip in eight patients. Six of the eight recovered a classic two-point discrimination of less than 6mm! with the advent of micro-vascular transfer of tissue, the great toe-to-thumb[30] and the second toe-to-thumb[31] re-constructions have also reported recovery of classic two-point discrimination that is better than it was in the toe prior to transfer.[32] Similar gains in tactile discrimination have been reported for microvascular transfer of dorsal first-second toe web space to the hand[33, 34] with improvement of from 15mm for the donor to 3mm for the recipient. These results can only be interpreted as demonstrating fulfillment of unrealized sensory potential in the transplanted tissue brought about by sensory re-education during and after nerve regeneration.

What is the origin of the term "sensory re-education?" In August of 1971 Doctor Curtis sent me a copy of a letter he had received from Group Captain C.B. Wynn Parry, Consultant Adviser in "Physical Medicine, Royal Air Force, Chessington, Surrey, England." The letter began:

I was sorry not to be at the meeting of the Society for Surgery of the Hand when you gave your Presidential address. I am particularly sorry as I read in the *Journal of Bone and Joint Surgery* of June, 1971 your experience with Doctor Dellon and Doctor Edgerton in sensory re-education. I would be most grateful for any published materials you have on this as to my knowledge you are the only other team to have worked in their field. I do not know whether you are aware that I have a fairly extended treatment of the importance of sensory re-education which I published in my book "Rehabilitation of the Hand," Butterworth, 1966… I hope you may find time to look through the relevant pages in my book as I would be very glad to know how our techniques compare.

In fact, Doctor Curtis had known of Wynn Parry's work, and once I had begun to discuss the project with him, he referred me to Wynn Parry's monograph.[35] My notation on my copy of that book indicates I bought it in June of 1969. Wynn Parry, to the best of my knowledge, was the first to utilize sensory re-education for patients with nerve repair in a formal program of rehabilitation. He wrote:

Although it had been accepted for many years that re-education of motor function is most important in the management of peripheral nerve injuries, little or no attention seems to have been paid to the problem of re-education of sensation after nerve suture. It is widely felt that the quality of sensation after median nerve suture to poor. At the most, protective sensation can be expected and in very rare cases is there an expectation of perfect two-point discrimination or stereognosis. In our experience over the last twelve years, in patients with combined median and ulnar nerve sutures who have had full-time treatment function is remarkably good. Our studies of such patients suggested that they were instinctively re-training themselves to learn to use their abnormal sensation for function. We therefore decided to apply sensory re-education techniques in a more formal manner in the Physiotherapy Department.[35]

Rehabilitation centers, however, had been applying the sensory retraining techniques for the decade prior to Wynn Parry's monograph. His techniques appear to be linear descendents from these. In 1955, the neurology section of the Minneapolis Veteran's Administration Hospital evaluated sensibility in 35 postcerebrovascular accident hemiplegics. Eighty percent had impaired sensation. Their length of hospital stay and ultimate recovery were found directly related to their recovery of sensation. In the rehabilitation unit, though, no definite sensory retraining program was used. The patient's sensibility was retested weekly. The authors concluded "re-training may play significant role in return of function."[36] Forster and Shields,[37] from the Neurology and Rehabilitation Departments at Georgetown University, reported in 1959 the first specific program for sensory retraining in hemiplegics. The technique was one of conditioning, with the patient alternately observing and blinded to his hand's activity. Activities included positioning of the digits, pinprick localization, weight discrimination with sandbags and attempted recognition of large objects of differing shapes and textures. In 1962, Vinograt et al.[38] utilized a modification of Forster and Shields' technique to retrain sensation in the hemiplegic hand. This group, from the Rehabilitation Department of the Wilmington, Delaware Veteran's Administration Hospital, used common household objects, like a ball, can opener, and keys for their object recognition. Patients were trained and retested daily for an average of 7 weeks. Results encouraged the authors to recommend sensory retraining "as an adjunct in the management of suitable patients."

The roots of re-education go back farther, however. In the Medical Research Council 1954 monograph on peripheral nerve injuries, for which Seddon was the editor, Ruth E.M. Bowden wrote an extensive chapter (54 pages) on "Factors Influencing Functional Recovery." Her final segment is subtitled "Re-education after Nerve Injuries." She wrote, "The aim of re-education of patients with nerve injuries is to aid the restoration of function in the damaged limb and facilitate the adjustment of the individual to his disability." She goes on, however, to discuss essentially only motor function rehabilitation and expresses almost pessimism over the potential of its sensory counterpart. "On the whole, there is no definite evidence to suggest the existence of compensatory adjustments in the central nervous system t faulty peripheral connections. However, there is an indication that constant usage may lead to greater manual dexterity even in the presence of such abnormalities."[39]

Possibly, the first to demonstrate that hemiplegics could be retrained were Ruch et al[40] in 1938. They reviewed their work in sub-human primates demonstrating that removal of the parietal lobe resulted in asterognosis. Then in the monkeys, and in humans following cortical loss, they demonstrated that sensory retraining or reconditioning resulted in some recovered function. This suggested the potential that led to the sensory retraining programs of Forster and Shields.

The roots of re-education go back even further. Just recently I was referred to an article by John S.B. Stopford[41] written in 1926. The reference to this article, and the only time I've ever seen it referred to, was in a recent paper by Horch.[42] The Stopford reference does not appear in the extensive bibliographies of Winkelmann, Sunderland or Seddon. Stopford was an ardent supporter of Henry Head's theories. The purpose of Stopford's paper was to provide an explanation for the two-stage recovery. Stopford notes, "We find the elements of sensation . . . which recover late and which most frequently show imperfect recovery . . . are those (epicritic) which Head has shown to have cortical representation." The protopathic sensations Stopford attributed to the thalamus. He went on:

> If the thalamus and sensory cortex provide a reason for the two stages of recovery, it is possible to understand why a longer period must elapse before the fibres subserving the cortical forms of sensation function correctly . . . a very much more complex readjustment and *re-education* (emphasis mine) must occur after regeneration of the fibres . . . In consequence of the inevitable disturbance of the intraneural pattern after suture, chance plays a considerable part in the success of the result, since a variable number of regenerating fibres must grow down the endoneural, perineural, or epineural connective tissues and be functionally lost, whilst others grew down heterogeneous peripheral fibres . . . Fibres previously concerned with transmission of impulses excited by

pain may frown down . . . "localization" paths . . . It is conceivable that after the lapse of time, a capable patient would by *re-education* overcome this and localize the stimulus more or less accurately. Such a period of *re-education* would explain the occurrence of an interval between the recovery of the crude forms (protopathic) and the higher forms (epicritic) of sensation . . . It seems possible that by *re-education* some recovery may follow at a later date.

With that amazing quote, I will leave the "roots" of re-education to a future "gardener" who may wish to dig deeper.

TECHNIQUES OF SENSORY RE-EDUCATION

This section is entitled technique *s*. There is no one technique of sensory re-education.

Sensory re-education is a method or combination of techniques that help the patient with a sensory impairment learn to re-interpret the altered profile of neural impulses reaching his conscious level after his injured hand has been stimulated.

In the normal state, stimulation of the hand by contact with the external environment stimulates the sensory receptors, a profile of neural impulses is elicited, these impact upon the sensory cortex, associate with previous memory or experiences, and ultimately become consciousness, a perception. After a nerve division and nerve repair, the same contact with the external world, the same stimulus, now elicits a different or an altered profile of neural impulses. When these reach the sensory cortex, they may find no match in the association cortex. Thus, the sensation is new, cannot be names, and may even pass unnoticed (Fig. 12.4).

Despite any future refinement in technical skill with nerve repair, altered peripheral sensibility is statistically inevitable (Fig. 12.5). With microsurgical fascicular repair, hopefully, the "majority" of regenerating axons will cross the suture, enter their own or a closure cousin's endoneurial tube, and distally reinnervate the correct type of sensory end organ. Some regenerating axons will arrive distally to find their former home destroyed, degenerated beyond salvage. Some regenerating axons will arrive distally to the correct local but find themselves in the wrong home. A former index fingertip Pacinian afferent may return to the index fingertip but reinnervate a Merkel cell-neurite complex, or a former index fingertip resident may find himself in the thumb. Then there will be the group of axons that either never cross the suture line and grow out of the epineurium to form a neuroma, or grow distally into the epi-, peri- or edoneurial connective tissue. These possibilities create the following potential alterations: (1) an absolute decrease in the number of normally functioning peripheral receptive fields; (2) a new set of abnormal peripheral receptive fields (wrong fiber/receptor combinations, one fiber reinnervating multiple receptive fields); (4) dysesthetia (axons trapped in scar at repair site) (Fig. 12.5)

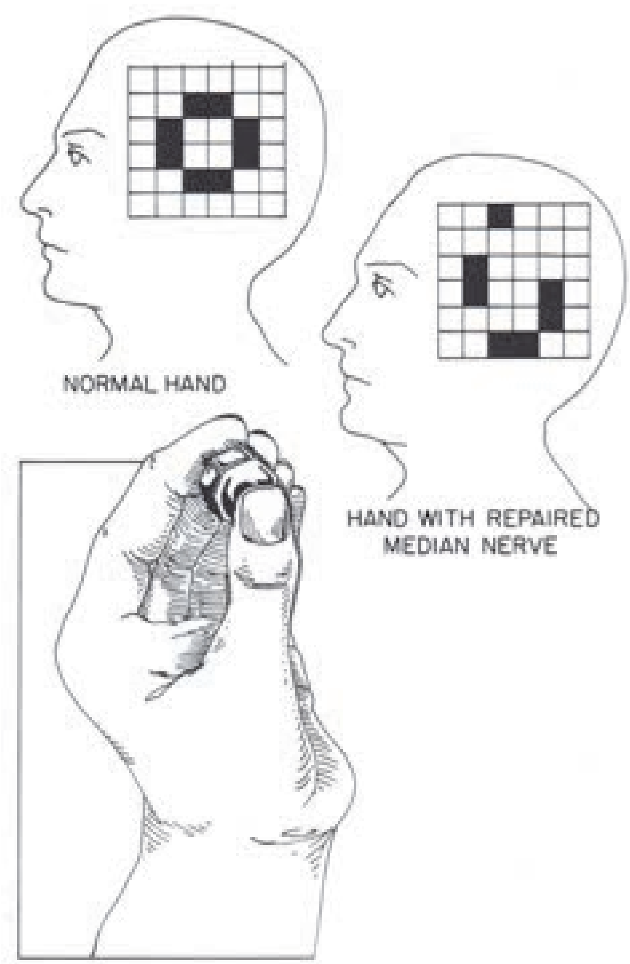

Figure 12.4. In the normal hand, a stimulus, such as this gripped bolt, elicits a profile of neural impulses which reaches the sensory cortex, and ultimately is perceived, as represented by the checkerboard pattern. After a nerve repair, the same stimulus elicits an altered profile of impulses, which reaches the sensory cortex. The new perception, the altered checkerboard pattern, may be so different from the previous one, that object recognition is at first impossible.

Refinements in surgical technique should be giving patients an increasing potential for sensory recovery. It is my belief that the present failure to demonstrate improved end results following nerve repair is less a failure of the surgeon to achieve fascicular alignment as it is a failure of the patient to realize the potential given to him at surgery. The goal of sensory re-education is to help the patient achieve the full potential for functional sensory recovery given to him by his nerve repair (Fig. 12.6)

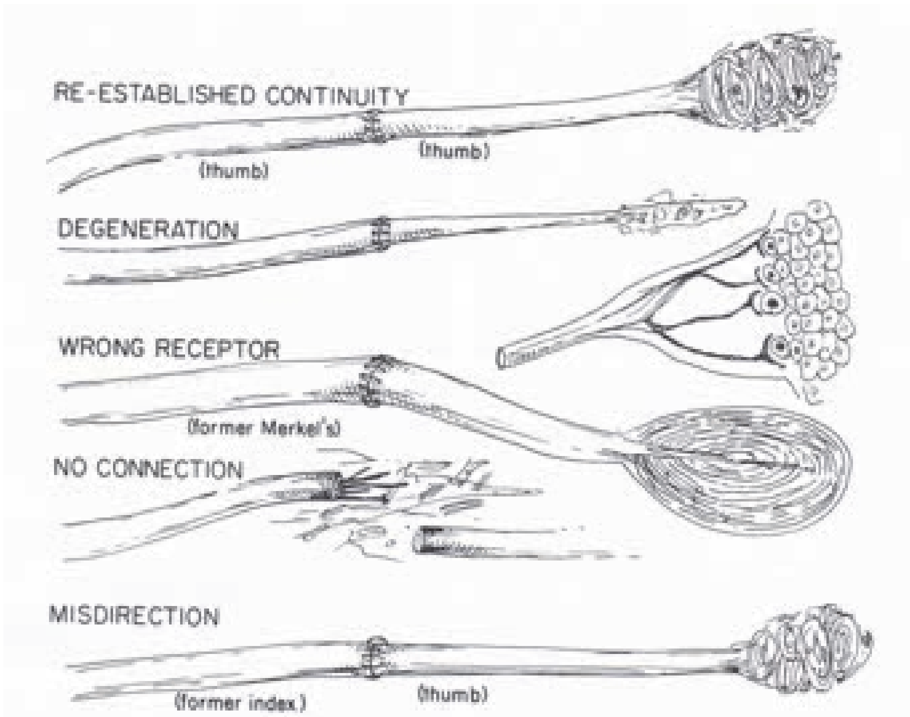

Figure 12.5. The inevitable altered profile of impulses. The majority of regenerating axons will re-establish continuity with the appropriate end organ in the appropriate digital area. However, some axons will arrive to find an irreversibly degenerated end organ, others will arrive at the correct digital area, but reinnervate the wrong end organ, which others will either never re-enter a distal endoneurial sheath or be misdirected to the wrong finger. Thus, a stimulus gives rise to a different profile of nerve impulses than this stimulus elicited prior to nerve repair.

The first published formal program of sensory re-education following nerve repair is that of Wynn Parry.[35, 43] In essence, blindfolded patients are given a series of familiar, large, household objects to identify. The time required for object identification is recorded and used as a basis of comparison during subsequent testing and training sessions. Tasks are increased in complexity as the patient improves. They are begun on coins, erasers, paper clips, keys cards, etc. if they can't recognize an object in 60 seconds they go on to the next, for 10 objects. Failing these, they begin with large wood blocks of varying weight, shape, and size, covered with different textured materials. If they still cannot identify the object, they are permitted to open their eyes, "study the object carefully and then feel it again with their eyes shut, thus trying to combine the mental with the visual picture. The patient carries out the same procedure with the unaffected hand so that he may compare the sensation on the two sides." Training is given daily or patients are asked to get someone to help them at home daily.

Figure 12.6. Conceptual basis for altered profile of neural impulses after nerve repair. *A*. The three people here are seen by stimulation of sensory receptors in the eye, causing neural impulses to be received in the visual cortex f the brain. These impulses are associated with previous visual memory patterns and given a name, e.g., Evan (Left), Marge (center), Glenn (right). The analogous series of events occurs normally in the hand, e.g. tactile gnosis. After a nerve repair, a number of axons never regenerate causing discrete loss of impulses from the previous pattern (*B*). After a nerve repair, a number of axons will regenerate to the wrong topographic area, i.e., index to thumb, or Evan to Glenn (*C*) after a nerve repair, a number of axons will reinnervate an inappropriate sensory end organ, creating unnatural combinations, of unknown potential, e.t., eye for nose, eye for an ear (*D*). Even in the microsurgical repair, all of these combinations occur to a degree (*E*) and in some repairs the resulting combinations *(F*) may create impulse patterns that are impossible to recognize. Sensory re-education can overcome much of this distortion, and allow recovery of tactile gnosis.

Following the appearance in the *Journal of Bone and Joint Surgery* of the abstract of my presentation on sensory re-education at the 1971 meeting of The American Society for Surgery of the Hand, I received many requests from hand surgeons and therapists for a copy of my "program." As mentioned earlier, the *Journal of Bone and Joint Surgery* had rejected our manuscript. Their letter of August 17, 1971 said in part, "All of us thought the study was pertinent to the practical concerns of a good number of our Journal's readers, but many of us thought that… the experimental plans did not sufficiently take into account one possible source of error—bias on the part of both subject and observer." The letter concluded, "We think your method and experience with it should first be shown to be acceptable to the physiologists and should appear in their literature as a valid study." I was undoubtedly biased. I was also in the midst of my surgical residency. I wrote up our program and sent off Xeroxed copies to all who requested them. Interestingly, in 1978 I was shown a book available through Sammon, Inc. which included this program as a chapter on sensory re-education.[44] They never asked our permission to publish it, but I thank them now for distributing it!

My program consists of a series of specific sensory exercises instituted at the appropriate time to the recovery process. One can't run before he can walk. The pattern of sensory recovery outlined in Chapter 7 may be thought of as the timetable on which to base the introduction of sensory exercises. Initiating an exercise before the appropriate fiber/receptor system has reunited can only lead to frustration and filure. Instituting the appropriate exercises at the appropriate time speeds patient recovery, builds patient confidence, and facilitates recovery of maximal function in the minimal time.

Early Phase Sensory Re-education

The pattern of sensory recovery is charted by evaluating sensibility (see Chapter 10) with the 30-cps tuning fork, moving-touch, constant-touch and the 256-cps tuning fork. The perception of these stimuli will recover in this same time sequence, i.e. 30 cps first, 256 cps last. When 30 cps and moving-touch have returned to an area, for example, the palm, early phase re-education may be begun. It is most critical to begin by the time recovery has reached the proximal phalanges. The goal at this stage is (1) to re-educate submodality-specific perceptions, movement versus constant-touch and pressure and (2) to re-educate misdirection or incorrect localization. The exercise simply is for the patient to use a soft instrument like a pencil's eraser, or someone else may use their fingertip to stroke up and down the length of the area being re-educated. The patient observes what is happening, shuts his eyes and concentrates on what he is perceiving, and then opens his eyes to confirm again what is really happening (Fig 12.7). He should verbalize to himself what he is perceiving as specifically as he can, i.e., I feel something moving up (down) my index finger near the palm.

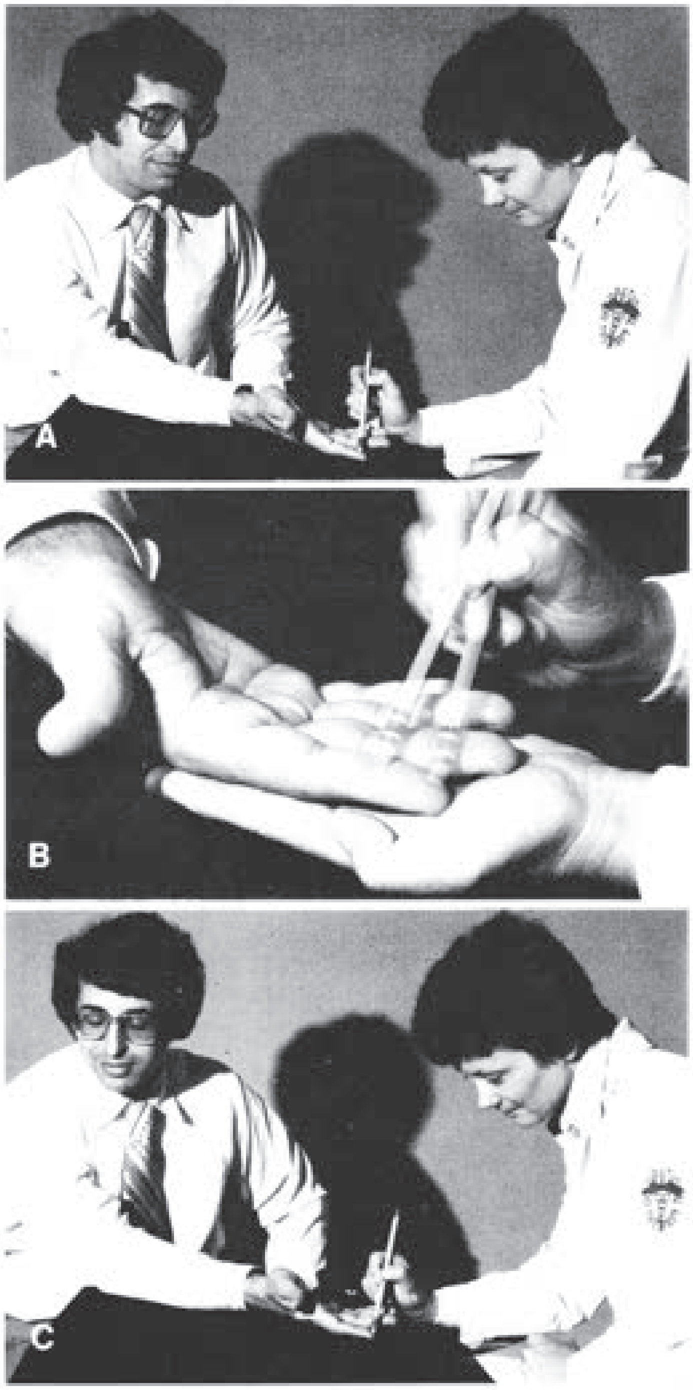

Figure 12.7. Early Phase Sensory Re-education. The perception of moving-touch is returning to the finger. The patient (*A*) directly observes the stimulus (*B*), a moving pencil eraser, on his fingertip, then (*C*) shuts his eyes (emphasized here by also turning the head), and concentrates again on the stimulus. At this point he should be telling himself, "I feel something moving on my index finger." This is repeated several times in each area recovering sensation. Goal is to (1) re-educate touch submodalities and (2) re-educate mislocalization.

When the patient can perceive constant-touch, the same type of Early Phase Re-education is done for his touch submodality, i.e., the eraser is pressed down into one spot on the palm or finger within the area of recovered constant-touch perception, and the patient first directly observes what is occurring, then shuts his eyes and repeats the stimulus, verbalizes to himself what he is perceiving, opens his eyes and reaffirms the stimulus/perception, again he should be saying "I feel something pressing (soft, hard) on my index finger near my palm."

How hard should the stimulus be pressed into the finger? Remember that the newly reunited fiber/receptor system is "immature, its threshold is therefore high, and early in the recovery of sensation more stimulus intensity must be used for perception to occur (see Fig 7.3). Press the moving or still eraser as hard as necessary for the patient to perceive constant-touch or movement. However, stimulus intensity should never be such as to evoke the perception of pain. We are not re-educating pain perception.

The patient should not stimulate one hand directly with the other. The patient's right index finger should not be used to stroke or press upon the patient's left palm or left thumb. If this were to occur, the patient would be receiving two sets of sensory information, one from each hand. At this early point in re-education, this only confuses the distorted sensory picture.

Who does Early Phase Re-education? We all do, the entire hand rehabilitation team. The surgeon, whenever he examines the patient, will be doing these exercises to ascertain for his own records the degree of recovery. This may be about once a month and should re-enforce the whole motivational/emotional system and the need for re-education. The hand therapist should be doing sensory re-education concomitant with motor re-education, range of motion, strength exercises, and massage. If there is dichotomy in the rehabilitation department with specific skills being assigned to physical and occupational therapy, a good workable arrangement we have found is for the physical therapist to do the motor re-education, including range of motion, strength, massage, whirlpool, ultrasound, etc., and for the occupational therapist to do the sensory re-education program. Certainly, any interested therapist or individual (mother, sister, boyfriend, visiting nurse) can be shown the sensory re-education technique and be "pressed" into service. The therapist should be seeing the patient at least once a week, if possible, for just 10 to 15 minutes to reinforce the goals, check the progress, provide reassurance, and establish that individual one-to-one contact that often makes the difference in the marginally motivated patient. The patient, himself, should be encouraged to practice Early Phase Sensory Re-education four times a day, even if just for 5 minutes a day.

The environment in which re-education is done is important. Janice Maynard, the therapist with whom our first sensory re-education work was done, has emphasized this.[45] A quiet room is essential. A soundproof room in the Hand Center is ideal. A bustling, noisy area is to be avoided. The patient is trying to concentrate on early, altered sensory perceptions. During this phase, if hyperesthesia or dysesthesia develops, specific desensitization should be begun concomitant with Early Phase Re-education.[45] Specific re-education exercises occasionally may need to be discontinued until a period of extreme "over-response" passes or is worked through. But, the exercise being used for desensitization, gently stroking with different fabrics, gentle tapping, etc., can be re-educational in themselves, and, conversely, the Early Phase Re-education exercises can help desensitize the mild case of hyperesthesia.

You may find a patient who recovers the perception of 30 cps at the fingertip while the perception of moving-touch remains in the palm. Or you may find the patient who recovers both 30 cps and 256 cps at the fingertip while perception of constant-touch remains in the palm and perception of moving-touch in the proximal phalanx. The patient has re-established the requisite fiber/receptor system for perception of moving-touch at the fingertip in the former, and for both moving- and constant-touch in the latter case. A "potential" gap exists. Within 2 to 3 of intensive Early Phase Re-education, this gap can be overcome (see Fig. 12.8)[5] In these situations, the tuning fork is your guide to instituting the specific sensory exercises. Once the perception of 30 cps has reached the fingertip, you need not wait to institute the movement exercises to the distal phalanx. Once the 256 cps has reached the fingertip, you need not wait to institute the constant-touch/pressure exercises to the distal phalanx. Early Phase Re-education should be introduced to the fingertip 4 to 6 months following a median or ulnar nerve repair at the wrist level.

Late Phase Sensory Re-education

Late Phase Sensory Re-education should be begun a soon as moving-touch and constant-touch can be perceived definitely and unambiguously at the fingertip with good localization. In our experience, this often can be as early as 6 to 8 months after median or ulnar nerve repair at the wrist.

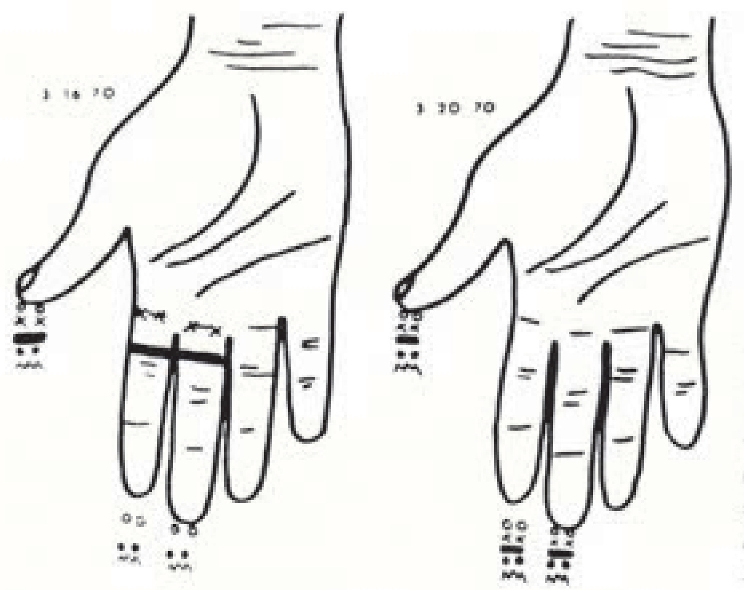

Figure 12.8. Early Phase Sensory Re-education. When perception of vibratory stimuli can be perceived at the fingertip and touch stimuli cannot (see text), a potential gap exists that can be filled quickly with specific re-education exercises. Legend (for this figure only) ***, 30 cps; 000, 256 cps; >>>, pain; xxx, constant-touch; ===, moving-touch. (Reproduced with permission from A. L. Dellon et al; *Plast Reconstr Surg* 53:297-305, 1974.[5])

It is never too late to begin Late Phase Sensory Re-education.

Beginning it too early leads to inevitable patient failure at the recognition tasks and heightens patient/therapist frustration. It is important to tell the patient at the beginning of this phase that he will continue slow improvement in his ability to recognize objects. He simply will not be physiologically ready to differentiate the smallest objects until 10 to 12 months after nerve repair at the wrist if he is "young" and has a good repair. It is critical to give the patient a timeframe for improvement so his expectations can be realistic.

The goal of Late Phase Sensory Re-education is to guide the patient to recovery of tactile gnosis, nothing less. If we expect less, we'll get less.

Sensory re-education cannot induce axonal regeneration. Sensory re-education can only help the patient achieve the fullest potential provided by the nerve repair. However, we do not know the consequences of improper fiber/receptor connections. For example, it is entirely possible, indeed probable, that a quickly-adapting former Pacinian afferent can reinnervate a Meissner corpuscle (which is, of course, the transducer for the other quickly-adapting fiber/receptor system) and form a functional unit. But, what happens if a quickly-adapting fiber enters a previous Merkel cell-neurite complex, or a slowly-adapting fiber enters a Meissner corpuscle? These may give rise to cortical level confusion, such as the type shown by Paul, et al. (Fig. 12.9)[46] or dorsal horn confusion, such as the type recently shown by Brushart and Terzis.[47] Furthermore, a regenerating axon, by virtue of it multiple axonal sprouts, may reinnervate receptor in two different areas, thereby having one fiber innervate two separate peripheral receptive fields. Such an occurrence has been demonstrated recently by Horch[42] and by Dykes and Tersiz.[48] Horch demonstrated a slowly-adapting fiber reinnervating more than one Merkel cell-neurite peripheral receptive field. Dykes and Terzis demonstrated a quickly-adapting fiber reinnervating two different Meissner afferent receptive fields, and another fiber reinnervating both a quickly-adapting and slowly-adapting peripheral receptive field (Fig. 12.10). The possibilities here for altered patterns of neural profiles are obvious, and create situations requiring Late Phase Sensory Re-education.

Re-education may enable central reorganization. Groups of fiber/receptors which otherwise would have been totally lot to meaningful perception, if not groups that would have interfered with meaningful perception, may be recruited, retrained, and provide meaningful sensory input. If re-education can achieve such "central reorganization"[21] of these types of peripheral fiber/receptor misconnections, then re-education conceivably could help the patient enhance or even exceed the potential given by the nerve repair.

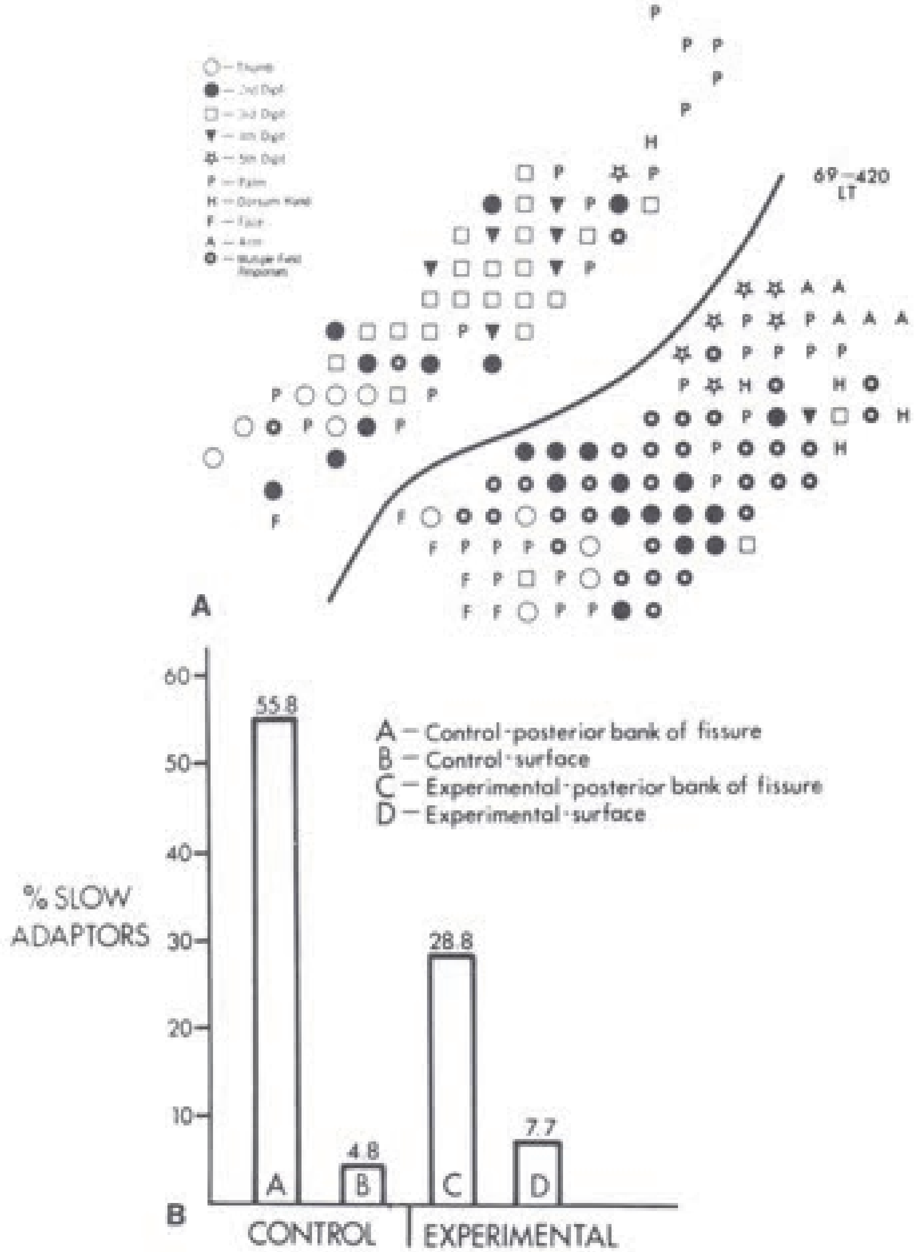

Figure 12.9. Cortical alterations following nerve repair. *A*, Example of evoked response recordings from postcentral gyrus of monkey after nerve repair demonstrating a large number of MFR (multiple field responses) in Brodman's area 1 (to right) and fewer number in area 3 (to left). The MFR represent a cortical neuron now representing more than one peripheral receptive field. *B* Demonstrates the average change in percentage of submodality-specific cortical neurons after nerve repair for bar *A* and *C* (area 3) and *B* and *D* (area 1). (Reproduced with permission from R. L. Paul et al; *Brain Res* 39:1-19, 1972[46])

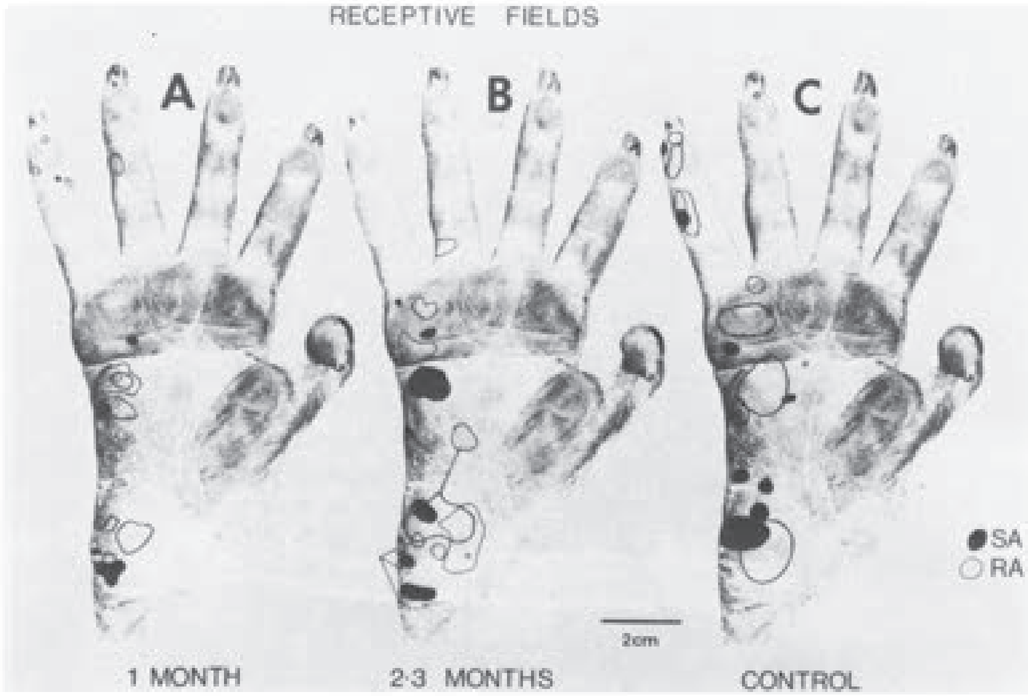

Figure 12.10. Peripheral alterations following nerve repair. The center hand has a single fiber reinnervating two rapidly-adapting peripheral receptive fields and another fiber reinnervating both rapidly-adapting and slowly-adapting peripheral receptive field. (Reproduced with permission from R. W. Dykes and J. K. Terzis: *J Neurophysiol* 42:1461-1478, 1979.[48])

Since the goal of Late Phase Sensory Re-education is recovery of functional sensations, the specific exercises should involve object identification. Tactile discrimination recovers progressively over time as measured by both classic and moving two-point discrimination.[25] Since, at any given time in the recovery process, moving two-point discrimination has recovered to a greater degree than classic two-point discrimination,[25] the object recognition tasks should incorporate movement. The tasks or exercises should be graded, beginning with the discrimination of larger object, with greater differences among them in size, shape, and texture, if possible, and progressing to finer and more subtle differences. Although it was generally accepted that tactile gnosis could not be present unless the classic two-point discrimination was less than 12 to 15mm, I have demonstrated recently[49] (see Chapter 10), that even in the absence of classic two-point discrimination (>25 mm) if moving two-point discrimination is less than 7 mm, a patient can identify objects by manipulating them between his thumb and index finger

Late Phase Sensory Re-education is begun with a set of familiar household objects, differing widely in shape, size, and texture (Fig. 12.11, top). Again, the sequence of object grasp with eyes open, eyes shut with concentration on perception, eyes open for reinforcement is utilized. After the patient has practiced with the object, the therapist may test him and record either the number of objects identified correctly or the time required (in seconds with a stop watch) for object identification. A record such as this provides evidence to the patient, therapist, and referring physician that progress is occurring. It gives the patient a goal "to beat" next time. It assists patient motivation. A chart, such as the one used for our standard timed object recognition test (Fig. 6.7), can be prepared for the set of household items, mimeographed, and be available to fill out and place into the patient's chart.

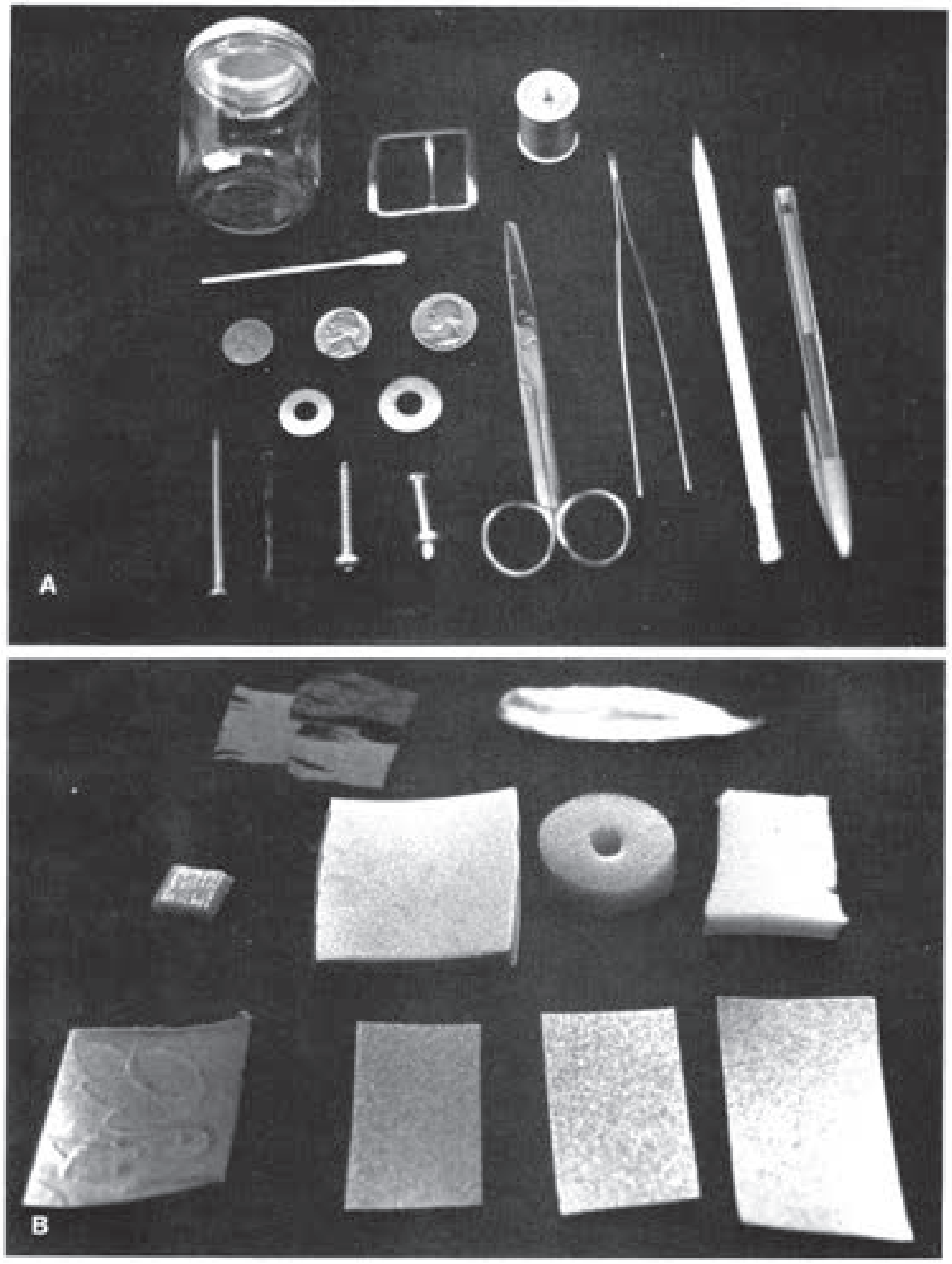

Figure 12.11 Late Phase Sensory Re-education. As moving two-point discrimination begins to return, and before classic two-point discrimination returns, movement must be incorporated into the object identification exercises. *A* Familiar household objects, differing markedly in shape, size, and texture are used, progressing to *B*, objects differing, for example, primarily in texture, such as felts, polyethylene, plastic, leather, and grades of sandpaper.

Late Phase Sensory Re-education is continued by progressing to objects differing largely in texture (Fig. 12.11, bottom) and then to objects that are smaller, differing in size and shape but not in texture, and requiring subtle discrimination (Fig. 12.12). At this stage, the patient will be clinically recovering classic two-point discrimination drops below 5 mm, patients will be able to identify the smallest objects correctly, although the objects may fall from the patient's grasp because the slowly-adapting fiber/receptor system has not regenerated and matured sufficiently. (It may never do so.)

It should be obvious that Late Phase Sensory Re-education also provides motor re-education (Fig. 12.13).

For the patient who worked before his injury, as soon as possible in Late Phase Re-education, activities that duplicate or incorporate work motions or activities should be included. To this end, a workshop within the Hand Center is ideal. A therapist with a background in industrial arts can design a program of workshop activities that coincide in sensory requirements with the degree of sensory recovery actually present. A Work Simulator, such as that recently designed by John Engalitcheff for the Raymond M. Curtis Hand Center at the Union Memorial Hospital in Baltimore, is ideal to practice a specific sensory grip before the patient is ready to try the actual tool at work (Fig. 12.14).

Who performs Late Phase Re-education? The entire hand team should participate. The hand surgeon during the office examination should test moving and constant two-point discrimination and object recognition. In so doing, reinforcement, reassurance, and motivation are provided to sustain the patient and back-up that the therapist has been doing at this point, the surgeon should be seeing the patient every 3 months. The therapist should be seeing the patient weekly, progressing to bi-weekly and perhaps monthly between the start of the Late Phase (6 to 9 months postrepair) and the patient's return to work. The therapist should be working through the Late Phase exercises, testing and recording the results of object recognition, encouraging and reinforcing the patient. At each session both classic and moving two-point discrimination are recorded. The patient should be practicing at home three to four times a day, 5 to 10 minutes each time. Frequent short sessions are more productive than longer, less frequent sessions. When the patient reaches the Fig. 12.12 stage, he is encouraged to carry the smaller objects in his pocket, or she in her purse, and to practice identifying them and picking them out during the day.

Late Phase exercises can be modified depending on the nerve involved. For the median nerve, all of the tests described above are applicable and essentially involve three-point pinch or gripping of the object between thumb, index, and middle fingers, and manipulating the object (Fig. 12.13). For ulnar or digital nerve injuries, a second person's presence during the exercise is helpful (Fig. 12.15) That person can place the object for recognition onto the surface of the fingertip being re-educated. Less precise but still helpful is for the patient to manipulate the object between the thumb and the fingertip being re-educated. Here the patient must try to concentrate upon the perceptions being transmitted via the injured finger instead of those coming from the thumb.

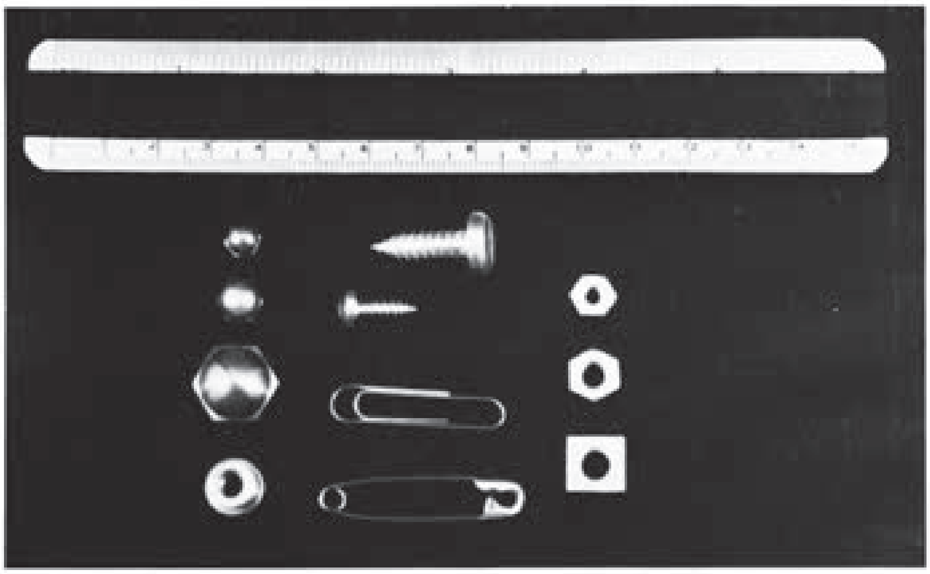

Figure 12.12. Late Phase Sensory Re-education. As moving two-point discrimination begins to return, smaller objects requiring more subtle discrimination in size and shape, but not texture, are used for object identification.

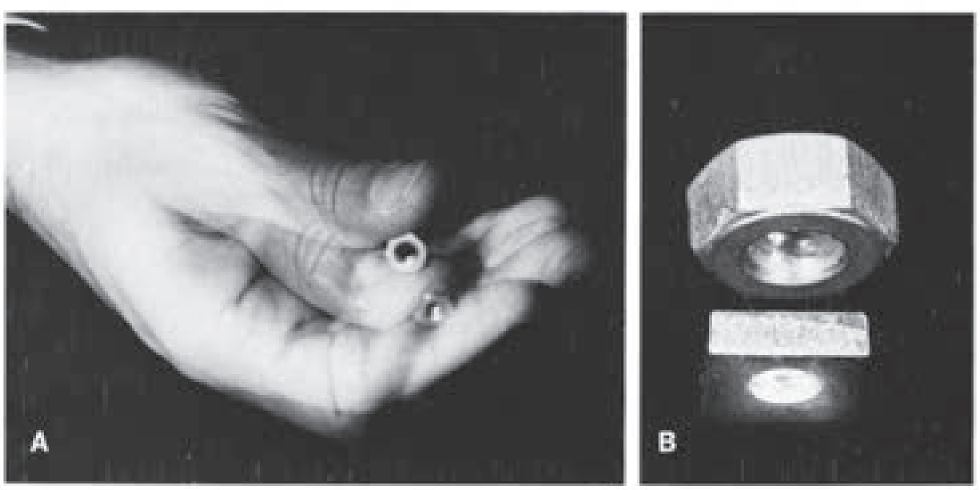

Figure 12.13. Median nerve-injured patients are re-educated with exercise involving manipulating the object for recognition between the thumb and index and/or middle finger (*A*). For final stages of re-education, patient attempts discrimination between the square and hex nut (*B*).

Other Techniques

At the onset, it was noted that there is no one technique. If it works for you and your patient, use it. Mansat and Delprat,[50] from Toulouse France, employ a program of sensory re-education modeled after ours. In addition to techniques discussed above, they show a patient receiving vibratory stimuli and placing geometric-shaped pegs into geometric-shaped slots. The success in training blind people to read braille was the inspiration behind Millesi's program of sensory re-education.[51] This program employs metal plates with standardized prominence, like braille, arranged in straight and wavy lines in a circle, square, and triangle. There are also plates with row of irregularly spaced dots. The patients practice *moving* their fingers along the figures and learning to identify them. The most recent sensory program of which we are aware is that described by Pegge Carter.[52] In addition to our program as outlined above, she adds "sensory bombardment" and the recognition of objects out of the visual field hidden in a sand or bean media (Fig 12.16).

If sensory re-education were being done on an investigational level, a technique that allowed comparisons would be important. When I did my first small series of patients in 1969, I allowed them to plateau in their recovery, and then instituted sensory re-education, late phase, with a few small hex and cap nuts in an attempt to standardize our procedure as much as possible.(5) Recently Colonel Reid and his hand therapists, Janet Werner, O.T.R. and Carl Sunstrum, O.T.R., presented the "preliminary results" of their sensory re-education program.[53] Their goal was to be able to relate the results of their program to the results of nerve repairs done in the past. They knew that classic two-point discrimination results improved with repeat testing and gave measurable results. Accordingly, their program employed the use of classic two-point discrimination testing, using a Boley gauge, begun at the time 256 cps had progressed to the fingertip. Patients received "twenty minutes of supervision twice a day for six weeks" in the military base hospital (excellent motivation for service men). The patients were also encouraged to carry a gauge with them and continue the training "while watching television or other educational endeavors. The results of these programs will be discussed below.

How long should sensory re-education be continued once the patient has recovered functional sensation? The program should be followed for a long time. If the patient returns to active work, or resumes housekeeping or hobbies, or is a child, the re-education is being continued at this level and no formal program is required. However, Wynn Parry[43] and Reid et al.[53] for median nerve repair, and Narakas[54] for brachial plexus repair, as well as I, have noted that if sensory re-education stops and the patient discontinues active daily use of his hand, the effect of the re-education is lost by the time the patient is next tested. Now this is "early on." If re-education is resumed, function is quickly recovered. After recovery has proceeded for "some time," the patient becomes increasingly able to maintain his re-educated status. Obviously, the program must be designed and modified on an individual basis.

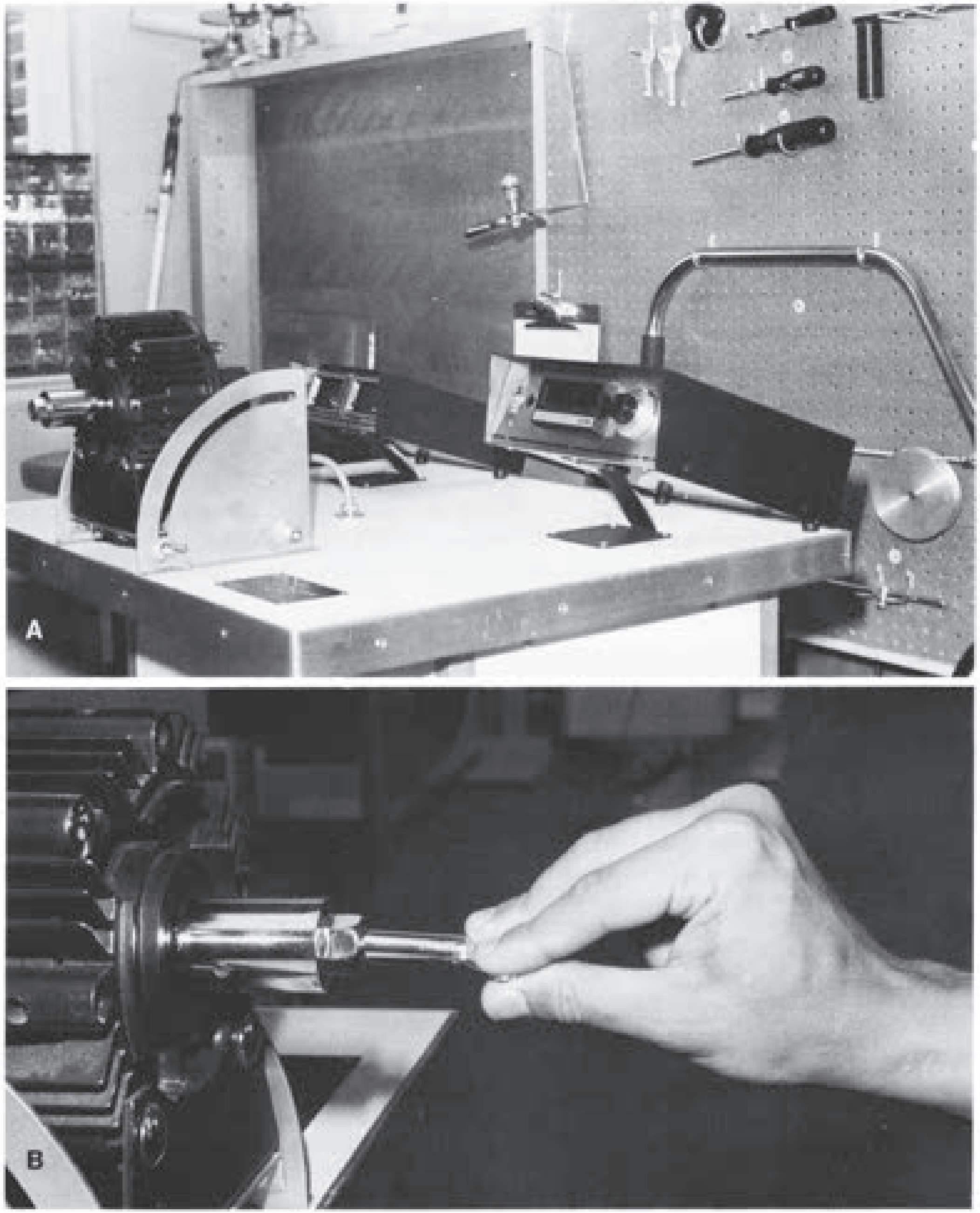

Figure 12.14. The Work Simulator *(A)* This rehabilitation machine was designed, and a prototype built by John Engalitcheff to fulfill the need of the Hand Surgeon and Hand Therapist as outlined by Raymond M. Curtis, M.D. Multiple attachments are available that connect to a calibrated resistance device. This permits a wide range of gross and precision sensory grips to be utilized with increasing strength *(B)*. The patients sensory re-education program can thus include actual work-simulated activities.[118]

Figure 12.15. Ulnar or digital nerve-injured patients are re-educated with exercises requiring object recognition, and this requires another person; e.g., a friend, placing the object upon the fingertip to be re-educated.

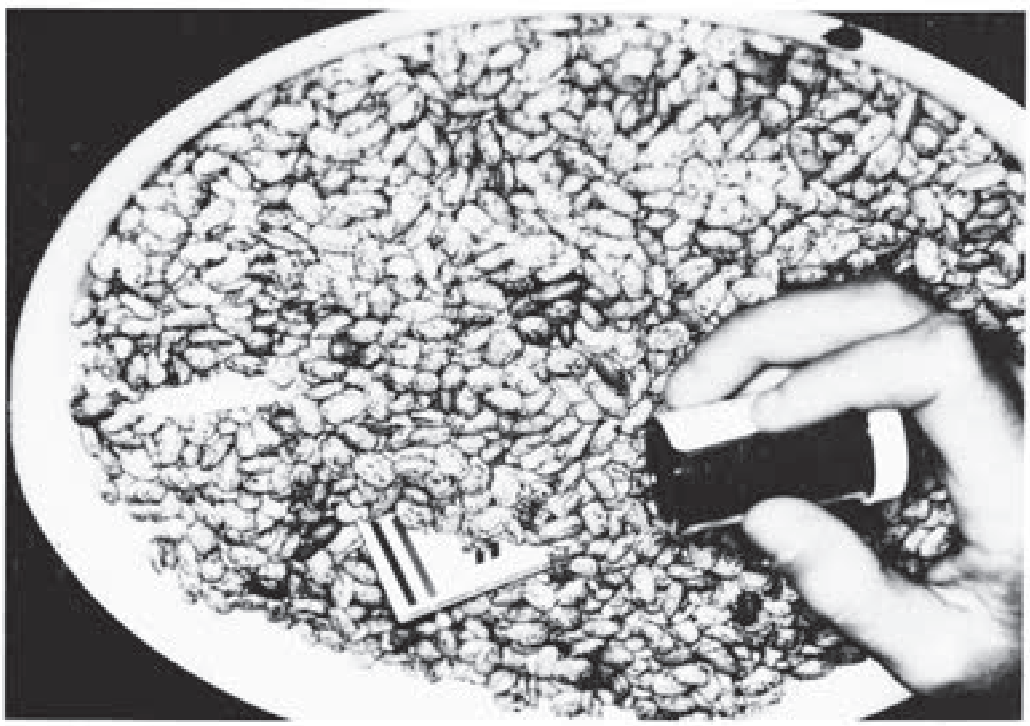

Figure 12.16. Bean media for sensory re-education. Patients, without visual clues, must identify objects within a pile of beans. (Reproduced with permission from M.S Carter: *Re-Education of Sensation.* Presented at the Hand Rehabilitation Symposium, Philadelphia, 1980[52])

RESULTS OF SENSORY RE-EDUCATION AFTER NERVE REPAIR

How may we ever know what is trues? What constitutes significant difference and what a chance observation? In the introduction to his monograph,[55] Seddon addressed this very subject. He wrote that he had the opportunity to conduct a controlled clinical trial," even with a prospective randomized design. He lamented that so many nerve-injured patients had passed his way, but he had not conducted this "scientific study." The answer to even "simple" questions like the "primary vs secondary nerve repair controversy" remained scientifically unanswered. He concluded that studies needed to be conducted properly and that even "forthright dogmatism was better than arguments based upon shaky statistics."

Moberg[56] attempted to answer the same question. He described the clinical investigator's dilemma:

> To progress in this complicated and difficult field, we must pick out almost ideal cases, with clean cuts, little scar tissue, and correct timing of the procedure. We must divide our cases into relatively small age groups… The level of the lesion must be approximately the same. Loss and recovery must be tested by reliable methods. The precise methods used must be described… test only one surgical variant at a time. Now where in the world can such an enormous number of nerve lesions be found? … I believe that our only way of getting ahead in the sensibility problems in this field will be to collect cases from several centres in the world. Then all these results… could be plotted on a curve corresponding to that of Onne …. If the results are above the "mean for average cases" it should mean "no improvement on present techniques." If the results are below this line, it might mean that the technical variation has contributed an improvement. This will be the way to get precise knowledge.

Moberg is suggesting the comparison of appropriately studied new patients with historic control. This is an accepted statistical comparison, but it assumes that only the variable studied has been varied over time. The historical control he suggests is "Onne's reported end results."[14] Onne measured classic two-point discrimination in ideal cases of nerve repairs and related these measurements to the patient's age (See Fig. 12.17). Onne reported that in general the classic two-point discrimination value recovered (in millimeters) equaled the patient's age (in years). Thus a graph of two-point discrimination versus age would be a straight line with a slope of 1.0. I will, below report the results of my own small series of end results after re-education on a graph such as Moberg suggested. Chapter 11 was written to serve as an historic control for comparison of end results of nerve repair previously reported with those of sensory re-education programs. I believe that this use of an historic control is as close as we will ever come to a "scientific comparison" of the effect of sensory re-education upon the result of peripheral nerve repair.

There is, perhaps, one other way we can know if something is "true." Felix Freshwater,[57] in a wonderful chapter on the history of Plastic Surgery, discusses the claim for historic priority. Who should receive the credit for a "discovery," Freshwater writes, the one who first discovers it or the one who makes it known throughout the world (if it happens that they are not both the same individual)? Freshwater quotes Owen[58] as saying: "He becomes the true discoverer who establishes the truth: and the sign of the proof is the general acceptance." I believe that sensory re-education has received "general acceptance." For the past 8 years, Sensory Re-education has appeared on the program of at least one, and usually more than one, nationally publicized hand symposium. For the academic year 1979-80, it has been on at least five national programs and one international program! Sensory re-education has been described in detail as a chapter in seven books[35,44,45,59-62] (not counting this one), described in brief in nine books,[63-71] and discussed as part of the methodology employed in 12 scientific reports.[5,25,50,51,53, 72-78] I am aware of active sensory re-education programs in the United States in Baltimore, Carville, Denver, Downey, Durham, Loma Linda, Louisville, New York, Philadelphia, and St. Louis. I am aware also of active sensory re-education programs in Australia, Austria, Canada, England, France, India, Japan, Sweden, and Switzerland. If, as Owen said, "the sign of the proof is in the general acceptance," then I believe sensory re-education can be said to be of proven value.

The *results of Early-Phase Sensory Re-education* are dramatic. The goal is to correct mislocalization and a lagging of moving- and constant-touch behind 30- and 256-cps perception in reaching the distal phalanx. Early Phase Re-education results in virtually 100% correction of mislocalization (*false* localization).[5, 56, 72] This can occur after just 3 to 4 weeks, if the patient has not previously been on a re-education program.[5] Once perception of the 256-cps stimulus is present at the fingertips, Early Phase Re-education has been 100% successful in the small group of patients we carefully studied and reported[5] in achieving the "catch-up" of moving and constant-touch perception to the fingertip. This occurred in less than 1 week of intensive re-education.

There are only two studies that give example of the end results achieved after nerve repair in patients who have been through a formal program of sensory re-education. Reid et.al.[53] presented data to the membership of the American Society for Surgery of the Hand via its Newsletter in 1977. They gave no percentage end results, but did document the course of recovery of sensibility in two patients (Fig. 12.18). These show recovery of normal classic two-point discrimination in less than 2 years in each case! Wynn Parry's results, also discussed below, are given in exact relationship to age for just one median nerve patient,[75] while it is given in this detail for four patients by Reid et.al.[53] In Figure 12.19, these five patients are plotted, as suggested by Moberg,[56] against Onne's results for the ideal nerve repair. All five points fall far below the line, indicating that not only are these results absolutely better in achieving sensory grades S3+ and S4, but they were achieved in 2 years after nerve repair, not 5 years. Since the remaining numbers of patients studied and exact results achieved are not specified in these studies, the overall results cannot be compared to the historic controls of Chapter 11 on a percentage basis. But note from Table 11.11, that these probably have been no adults previously reported who recovered to the S4 level.

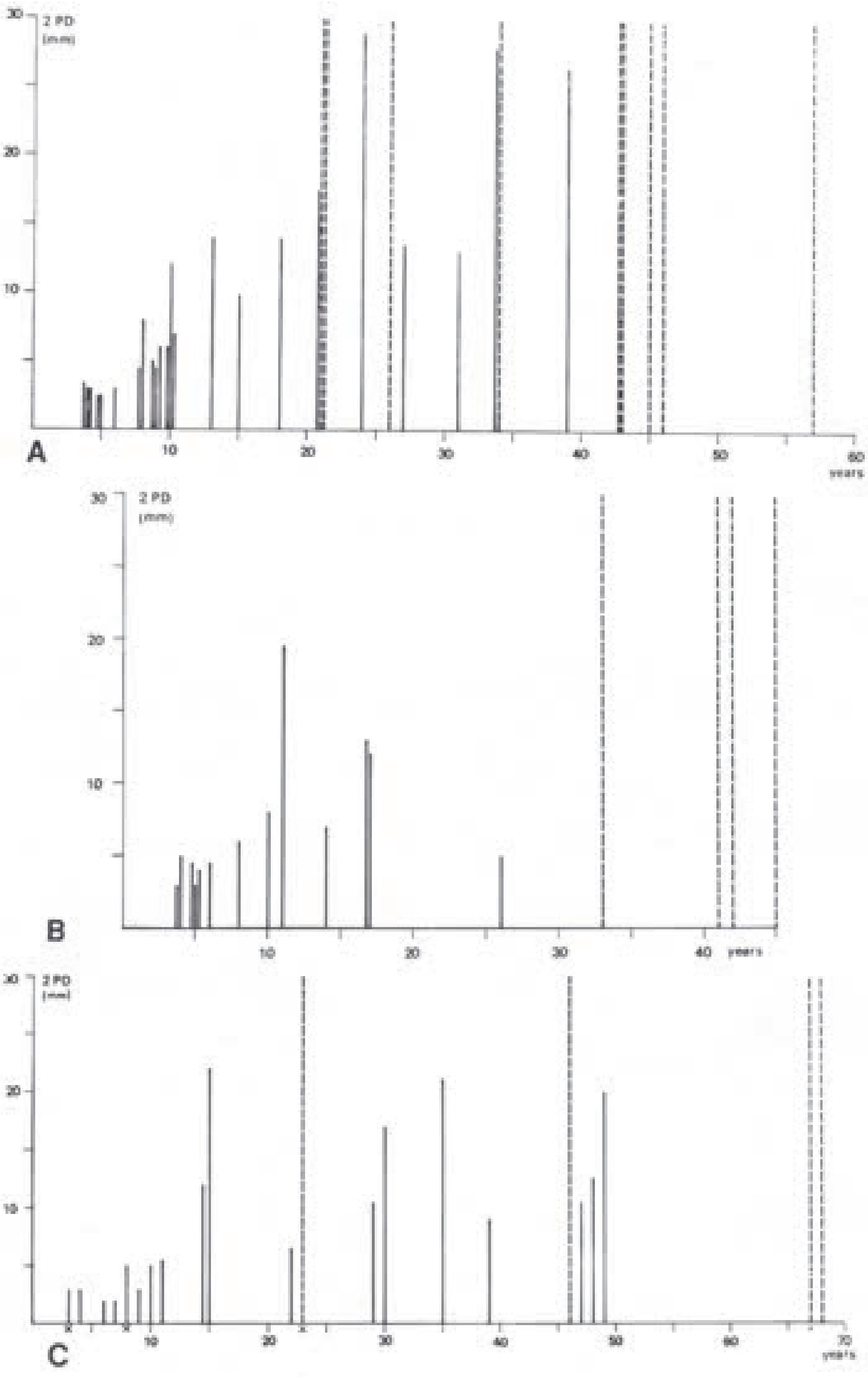

Figure 12.17. Onne's end results of nerve repair in ideal cases related to age (at time of repair) for median (*A*), ulnar (*B*) and digital *(C)* nerve repairs. Each line represents one patient, and dotted lines have 2PD greater than 30 mm. These results have been interpreted as demonstrating that 2PD is recovered in millimeters equal to the patient's age. (Reproduced with permission from L. Onne: *Acta Chr Scand [Suppl]* 300, 1962[14])

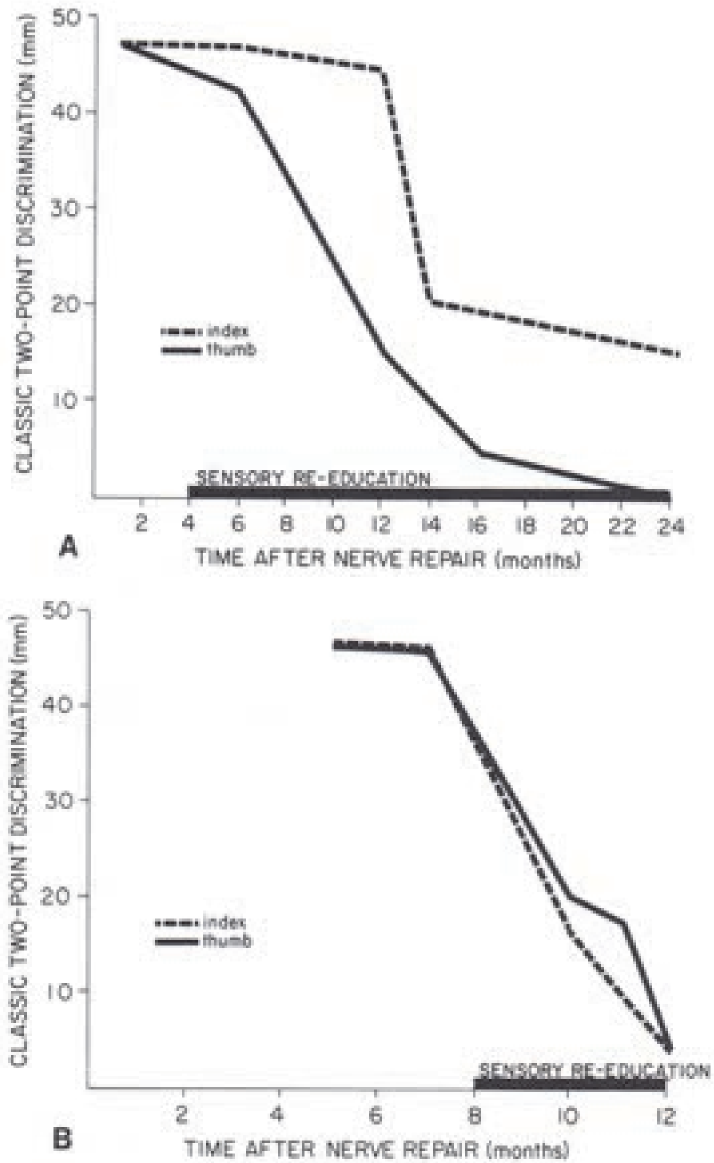

Figure 12.18. Late Phase Sensory Re-education results. *A*. Patient, L.M., 26 years old. *B*. Patient, J.H., 21 years old. Both with primary median nerve repair in distal forearm. Examples of results achieved with formal program of Late Phase Sensory Re-education. (Adapted from R. L. Reid, et al.[53])

The *results of Late-Phase Sensory Re-education* are also dramatic. Using Chapter 11's historic controls to compare the end results of nerve repair patients who have not had sensory re-education, we can make the following comparisons with Wynn Parry's results.[35] Compare Chapter 11's summary table, Table 11.13, with Table 12.1. For the historic control, adult civilian nerve repairs, 33% of median and ulnar nerve repairs recovered S3+. Wynn Parry'ss patients did too. None of the historic control adults achieved level S4. Wynn Parry reported that 50% of his median and 25% of his ulnar nerve patients recovered near normal sensation. The only other reported Late Phase Sensory Re-education results are those of Wilgis and Maxwell[77] for patients with digital grafts. Again, compare Chapter 11's summary table, Table 11.13, with Table 12.1. Of the historic controls for digital nerve grafts, 20% recovered to S3+ and 9% to S4. With sensory re-education, Wilgis and Maxwell reported recovering S3+ in 33% and S4 in 67% of their patients!

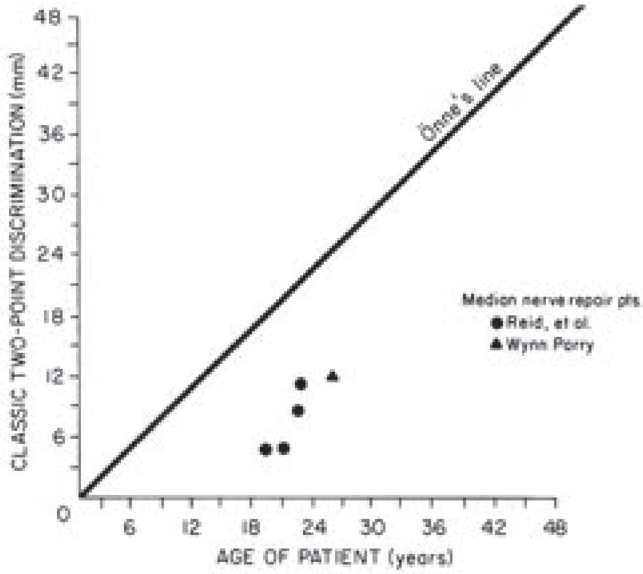

Figure 12.19. Late Phase Sensory Re-education results. Individual cases given as examples of the end results of their sensory re-education program by Wynn Parry[75] and Reid et al,[53] plotted as suggested by Moberg.[56] Diagonal line represents graph of Onne's results of ideal cases of nerve repairs.[14] Patient points falling below the diagonal line are those with results better than expected from repair of the "ideal nerve suture at five years."

Table 12.1
Results of Late Phase Sensory Re-education in Patients Following Nerve Repair

Reference, Date	Type of Trauma	Repair Timing	No. of Cases	Age	% Children	Follow-up (yr)	Motor Recovery (%) M 2	M 3	M 4	M 5	Sensory Recovery (%) S2	S2 +	S3	S3 +	S4
Median nerve repair															
35, 1966	Civilian	—[a]	—	—	—	2	—	25	50	—	—	—	—	33	50
75, 1976	Civilian	—[a]	23	—	—	3	—	—	—	—	—	—	—	—	—
53, 1977	War	All	150	Adults	—	—	—	—	—	—	—	—	—	—	—
Ulnar nerve repair															
35, 1966	Civilian	—[a]	—	—	—	2	—	—	40	40	—	—	—	50	25
Digital nerve graft		Gap Length					Nerve Block								
77, 1979	Civilian	1–2.5 cm	12	17–54	0	1–2	Yes				0	0	0	33	67

[a] Only examples of individual cases that demonstrated excellent response to re-education were reported. No statistics were reported (see Fig. 12.19).

I have just two criticisms of Wynn Parry's studies. He does not give quantitative data in terms of numbers of patients, or how long it took them to recover. He just reports, "50%" for example. The theoretical basis of his sensory re-education program is pattern theory. He believes the skin is reinnervated at random, and that the patient must learn this new pattern. This, as pointed out to me by Julia Terzis,[79] is different from the specificity theory, upon which my entire sensory exam and re-education program are based that is, reinnervation of specific end organs must occur, as explained earlier in this chapter and in Chapters 3 and 5. Of course, Wynn Parry's conclusion is identical to mine, namely, that patients need sensory re-education after nerve repair. The implementation of our two programs does differ. As per his more nebulous pattern theory, his program is non-specific. My program applies specific sensory exercises at the appropriate time in the recovery process.

Results of Late Phase Sensory Re-education: Personal Series

In this section, I will report the results achieved with 42 patients. These represent all the patients I have re-educated personally since I began in 1969, and who continued in the program for at least 1 year after their nerve repair. Most of these patients went through both early and late phase sensory re-education these patients include 16 median, 9 ulnar, and 17 digital nerve repairs. The patient's individual data, including age, type of repair or graft, follow-up interval, and tactile discrimination testing are listed in Tables 12.2, 12.3, and 12.4. the median and ulnar nerve repairs were done, to use present terminology, as microsurgical grouped fascicular repairs and the digital nerves by microsurgical epineurial repair (except for median cases 1 and 2, and ulnar case 1, which were done as microsurgical epineurial repairs). Many of the early cases in the series were done by the Plastic Surgery residents at Johns Hopkins, who were kind enough to allow me to test and re-educate their patients after the nerve repairs. I re-emphasize that this series is a personal series in which patients were seen often monthly, by myself. This kept even those with low intrinsic motivation working (and me too!)

The data in this personal series is first analyzed as suggested by Moberg, against the age line devised by Onne[14] for ideal nerve repair cases as evaluated at 5 years after their nerve repair. However, as seen in Tables 12.2, 12.3 and 12.4, the mean follow-up for the median nerve (at the wrist) patients is 17 months, for the ulnar nerve (at the write) patients is 19 months, and for the digital nerve patients is 14 months. As is evident from Figures 12.20, 12.21, and 12.22 for median, ulnar, or digital nerves, respectively, this analysis demonstrates that *all* patients who received sensory re-education did better than the ideal result predicted for their age. Even the two patients with high median and ulnar nerve lesions did far better than the predicted age-matched low lesion![§]

[§] Although I am biased I believe that if statistics could be applied to this type of data, I am sure they would demonstrate that sensory re-education made a statistically significant difference.)

Table 12.2
Results of Sensory Re-education Median Nerve (Dellon's Series)

Patient	Age at Repair	Type of Repair	Follow-up (mo)	Two-Point Discrimination (mm)	
				Moving	Classic
1	28	Primary	16	ND[a]	5
2	49	Primary	18	ND	6
3	20	Primary[b]	36	3	10
4	34	Primary	24	3	9
5	20	Primary	23	2	4
6	37	Primary	14	2	10
7	19	Primary	12	3	5
8	21	Primary	12	3	3
9	10	Primary	12	2	3
10	19	Primary	12	4	8
11	49	Primary	12	3	5
12	60	Primary	18	4	25
13	30	Primary	22	4	13
14	27	Primary	17	4	15
15	29	Primary[c]	12	6	19
16	30	Primary	18	3	5

[a] ND, not done.
[b] Plexus level.
[c] Elbow level.

Table 12.3
Results of Sensory Re-education Ulnar Nerve (Dellon's Series)

Patient	Age at Repair	Type of Repair	Follow-up (mo)	Two-Point Discrimination (mm)	
				Moving	Classic
1	18	Primary	18	ND	2
2	20	Primary[a]	36	9	15
3	17	Primary	24	2	7
4	20	Primary	23	2	6
5	16	Primary	15	2	5
6	35	Graft	13	6	20
7	27	Primary	17	2	5
8	29	Primary[b]	12	6	18
9	9	Primary	24	2	4

[a] Plexus level.
[b] Elbow level.

Table 12.4
Results of Sensory Re-education Digital Nerve (Dellon's Series)[a]

Patient	Age at Repair	Type of Repair	Follow-up (mo)	Two-Point Discrimination (mm)	
				Moving	Classic
1	47	Primary	18	ND	6
2	57	Secondary	22	5	5
3	24	Graft	12	4	6
4	18	Primary	12	2	4
5	18	Secondary	12	7	11
6a	46	Primary	15	6	10
6b	46	Primary	15	8	18
7	20	Graft	12	4	5
8	21	Graft	14	3	6
9	35	Primary	12	3	6
10	61	Primary	22	2	5
11	49	Graft	12	3	5
12	22	Primary	18	2	2
13	52	Graft	12	3	5
14a	28	Primary	12	3	4
14b	28	Primary	12	3	5
14c	28	Primary	12	3	6

[a] Results after nerve block of intact digital nerve. Block was not done if both digital nerves were repaired.

Table 12.5
Results of Sensory Re-education Dellon's Series Summary[a]

	No. in Group	Degree of Recovery		
		S3 (%)	S3+ (%)	S4 (%)
Median				
Total series	16	12	38	50
Adult, wrist level	13	7	39	54
Ulnar				
Total series	9	22	22	56
Adult, wrist level	5	0	20	80
Digital				
Total series	17	6	12	82

[a] Patients are less than 2 years after repair.

The data in this personal series can be analyzed also in comparison with the historical controls for adult civilian peripheral nerve repair, without sensory re-education, as summarized in Table 11.11. Historically 33% of low median and ulnar adult nerve repairs recover to S3+, and 0% to S4 by 5 years after nerve repair. In my total series 38% of median and 22% of ulnar nerves recovered to S3+ and 50% of median and 56% of the ulnar nerves to S4 (Table 12.5). If just primary adult repairs at the wrist level are considered, then 39% of median and 20% of ulnar nerves recovered to S3+ and 54% of median and 80% of ulnar nerves recovered to S4 in less than 2 years after nerve repair. For the historic control digital nerves, 48% recovered S3+ and 11% recovered S4 (the adult results for this group are really poorer because 12% of these were children) by 5 years after nerve repair. In my series of adult digital nerve repairs, 12% recovered to S3+ and 82% to S4 by 2 years after nerve repair. These results are far superior to the historic control.[**]

In summary, the success of sensory re-education in patients recovering from nerve repair has been demonstrated, in general, by the worldwide acceptance of the technique, and in particular, by the results published in the few studies available. The success achieved with sensory recovery is in both the percentage of patients achieving the higher level of recovery (S4) and in the savings in time (1 to 2 years, instead of 5) in which this level is achieved. This is schematically represented in Figure 12.23.

OTHER APPLICATIONS OF SENSORY RE-EDUCATION

Replantation

Because of the newness, excitement, and curiosity that surround the replant patient and his replant, more rehabilitation and more home care are usually devoted to these nerve repairs. This intention may be secondary or intended, but I suggest that each replant receives enough attention to be considered as having received sensory re-education. If they have not received this attention, certainly they should.

There have been three reports published of digital replantation in which the report has gone beyond the concern with replant survival and evaluated sensibility in terms of classic two-point discrimination.[80-82] The Louisville group has stated that their replant do receive formal sensory re-education.[83] The Australian[84] and Duke[85] groups have patients who have been exposed variably to formal sensory re-education, but who, nevertheless, have received the attention, referred to above, that is unique to the replant patient.

I suggest that the replant patients be considered as having been re-educated. The results of these three studies[80-82] appear in Table 12.6. By comparison with Table 11.11, it may be seen that the replanted digits with sensory re-education are recovering a greater degree of sensation than did the historic control group of digital nerve repairs.

Toe-to-Thumb Transfers

Foucher et al,[78] have reported most recently a series of toe-to-thumb transfers in which a formal program of sensory re-education was incorporated in the postoperative rehabilitation. Four patients were re-educated and followed sufficiently long to evaluate (8 to 15 month range with a mean of 10.5 months). These patients had classic two-point discrimination values of 3, 4, 4, and 7mm in contrast to the classic

[**] I have done a chi-square test on these data although I am sure a statistician would shudder at the assumption that these are all comparable groups. However, I know no other way to compare these data. The value is $p<0.001$ for each group)

two-point discrimination values of 14, 13, 12, and 15mm in the contralateral toe pulp. Four patients in the series did not receive sensory re-education. Their values were >15, 6, 10 and 14mm for a comparable follow-up period in contrast to the values of 14, 12, 17, 13 mm in the contralateral toe pulp. Clearly, sensory re-education has a role to play in these new procedures.

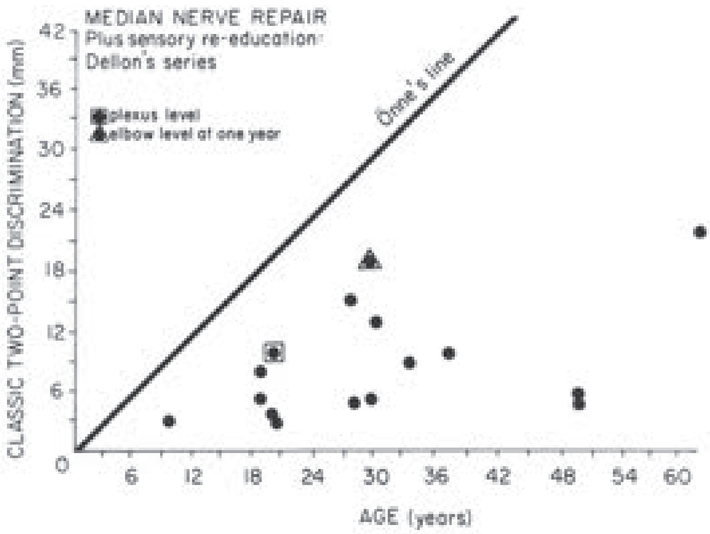

Figure 12.20. Late Phase Sensory Re-education results: median nerve. Patients are charted in relation to Onne's line, which is the 5-year postoperative result of the ideal nerve repair (measured in classic two-point discrimination) plotted against patient age. Patients are from Dellon's personal series. Note that all points are below Onne's line. This means that for each patient, the final result is much better than previously achieved by surgery alone. Sensory re-education permitted these greatly improved results just 1 to 2 years after nerve repair.

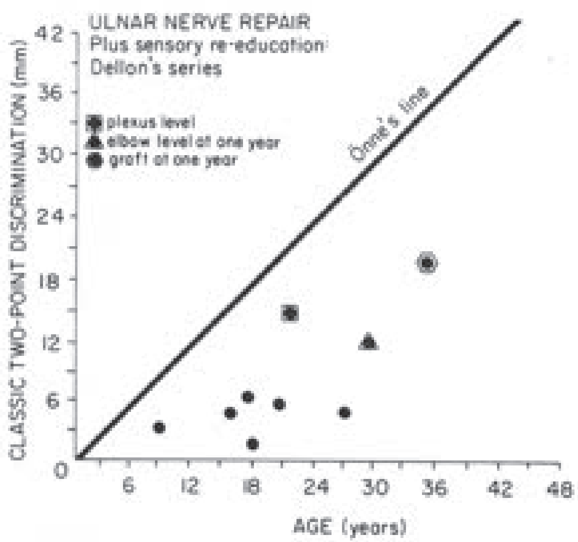

Figure 12.21. Late Phase Sensory Re-education results: ulnar nerve. See legend for Figure 12.20.

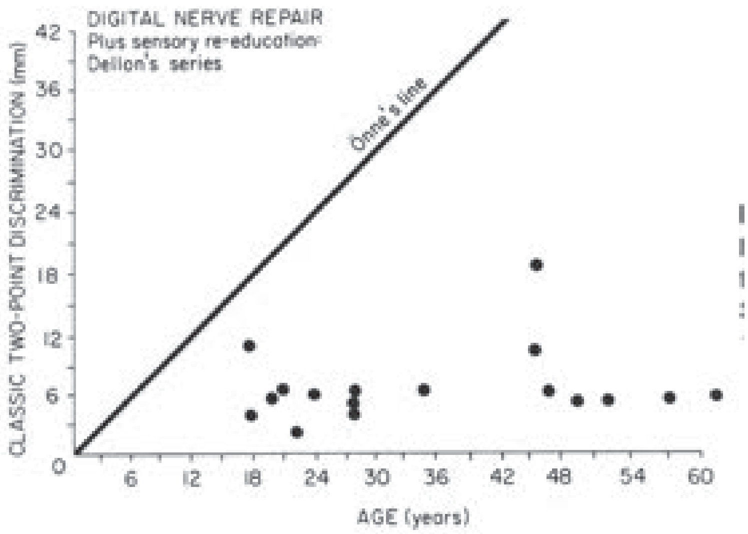

Figure 12.22. Late Phase Sensory Re-education results: digital nerve. See legend for Figure 12.20.

Cross-Finger Flaps

The reults of cross-finger flaps in terms of recovered functional sensation have been reported in general to be two to three times the normal classic two-point discrimination of the contralateral fingertip (27,86,87) (These papers cannot be put into the %S3 or %S4 terminology). Others have commented upon the poor sensory recovery in these flaps.(88-91) Kleinert et al.(74) reported on a series of 20 children (less than 12 years of age) and 36 adults (greater than 12 year of age). These patients received postoperative sensory re-education. Ten percent of the children and 33% of the adults recovered to a S3+ sensory level. Ninety percent of the children and 42% of the adults recovered to a S4 (normal) sensory level.(74) These are the best reported results of cross-finger flaps of which I am aware.

How can sensory re-education benefit cross-finger flaps? As discussed in Chapter 2 and demonstrated at the end of Chapter 5, distal dorsal skin has rudimentary Meissner corpuscle as well as hair follicles. The dorsal skin from the dorsal cross-finger flap is reinnervated and connections, of one form or another, are made. Certainly, the total number of normal functional fiber/receptor systems maturing is greatly reduced. But, for the potential is there for mechanoreceptor function. This provides the basis and potential for re-education of sensation.

SPASTIC, HEMI- AND TETRAPLEGICS

The extent of sensory recovery possible in these patients has been studied very little. The pioneering work in retraining sensation in hemiplegics following cerebrovascular accidents was reviewed above under the "Roots of Re-education" section.

My experience with one patient has convinced me of the potential for functional sensation that may be present in these patients.

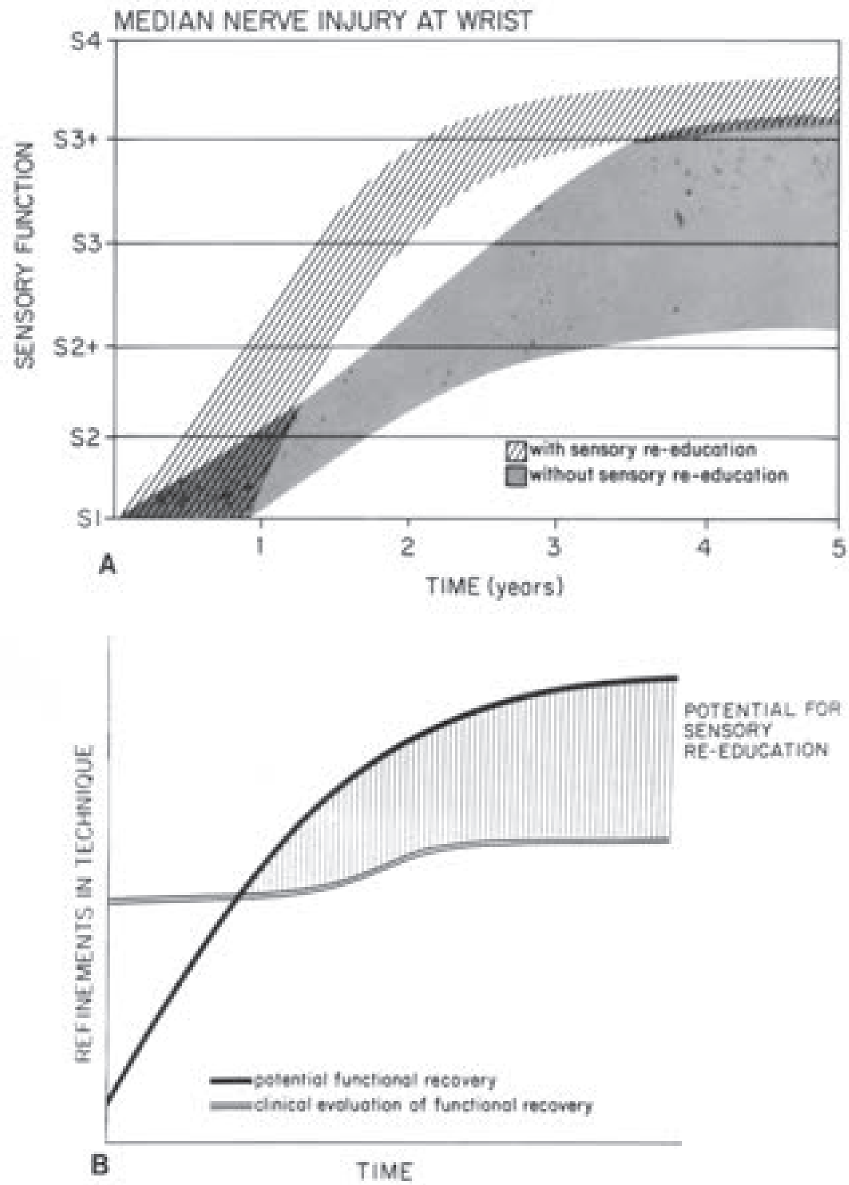

Figure 12.23. Results of sensory re-education program. Graphs demonstrate ability of sensory re-education to help more patients achieve the highest level of sensory recovery (S4) in the shortest amount of time.

Table 12.6
Results of Replants

Reference, Date	Type of Trauma	Repair Timing	No. of Cases	Age	% Children	Follow-up (yr)	Sensory Recovery (%)				
							S2	S2+	S3	S3+	S4
80, 1977	Civilian	All	70	1–70		¾–6	2		8	90	
81, 1978	Civilian	All	35	4–47	14	1–5	0	28	20	26	26
82, 1980	Civilian	All	25	2–72	13	1–3	0	26	13	9	52

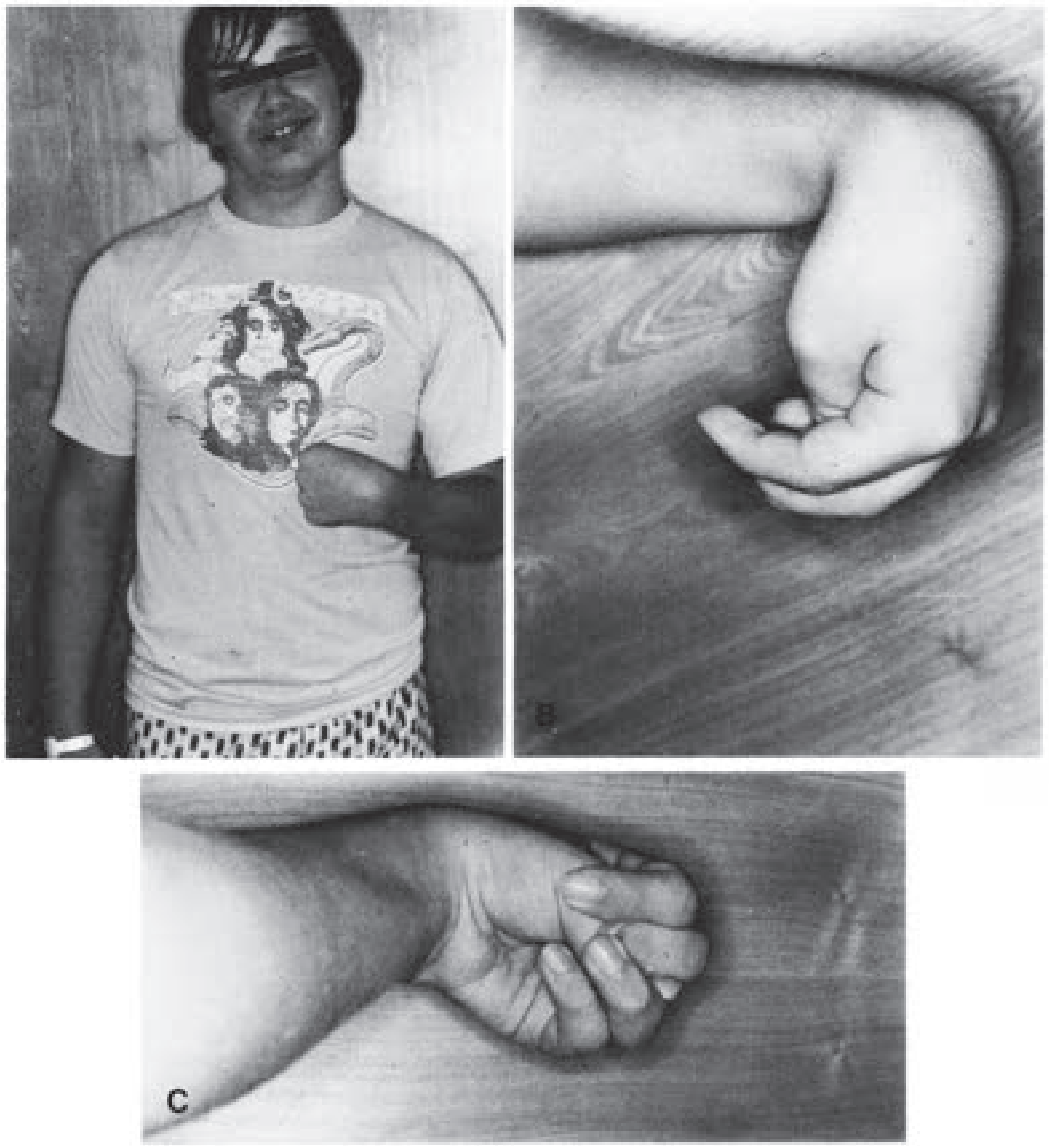

Figure 12.24. Spastic hemiplegic. *A*, Age 17 with posttraumatic left spastic hemiplegia. *B* and *C*, Note complete loss of use of fingertips, representing total sensory deprivation Evaluation of sensibility demonstrated no constant-touch perception or classic two-point discrimination. There was moving-touch and 30-cps and 256-cps perception, but no moving two-point discrimination. Tactile gnosis was absent.

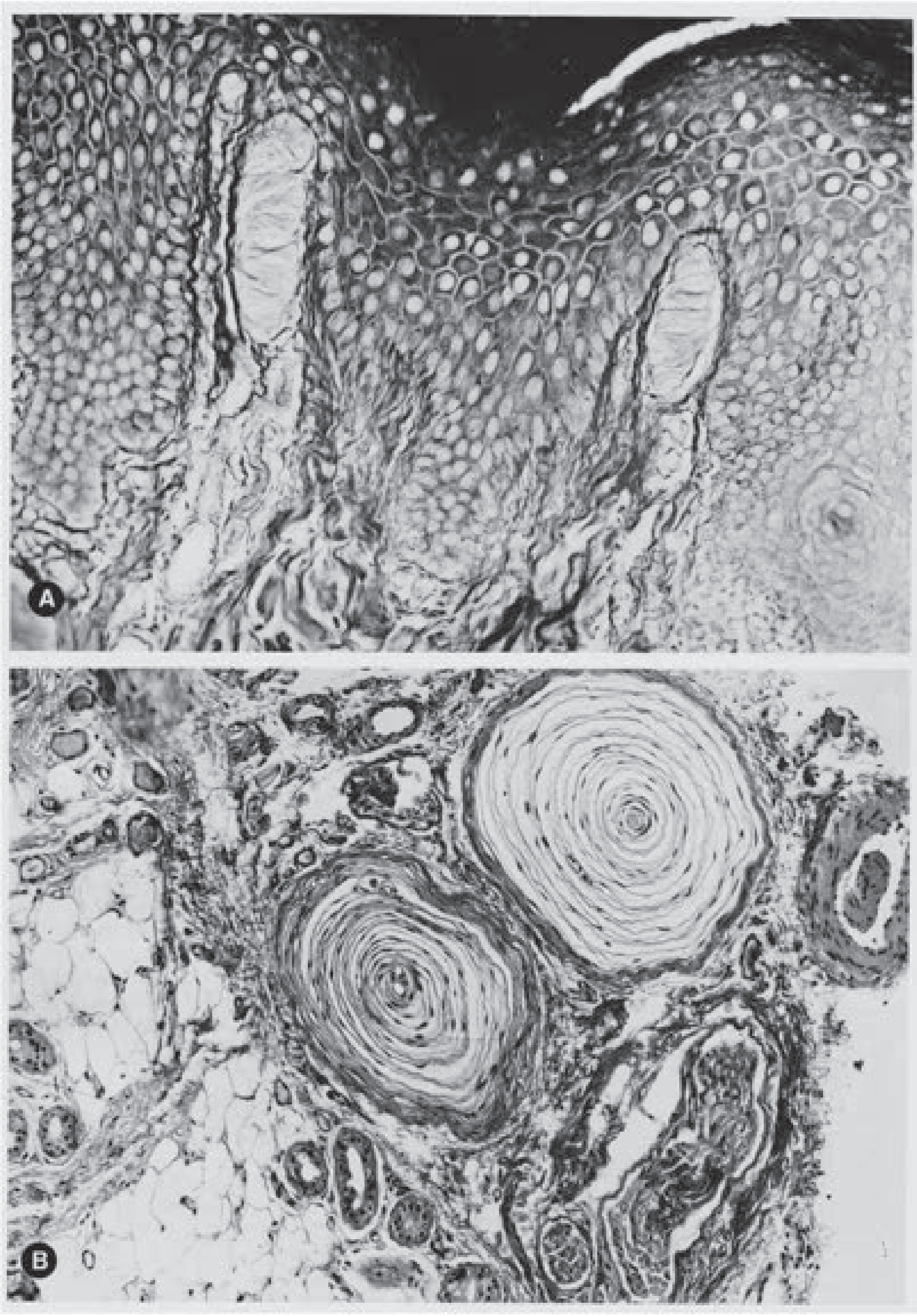

Figure 12.25. Spastic hemiplegic. At time of release of the thumb-in-palm deformity and tendon transfers, the middle fingertip was biopsied. Light microscopy demonstrated abundant innervated Meissner corpuscles (*A*, Silver stain; x64), two innervated Pacinian corpuscles (*B*. hematoxylin and eosin stain; x64), but few if any Merkel cell-neurite complexes (arrow)(C, Silver stain; x125).

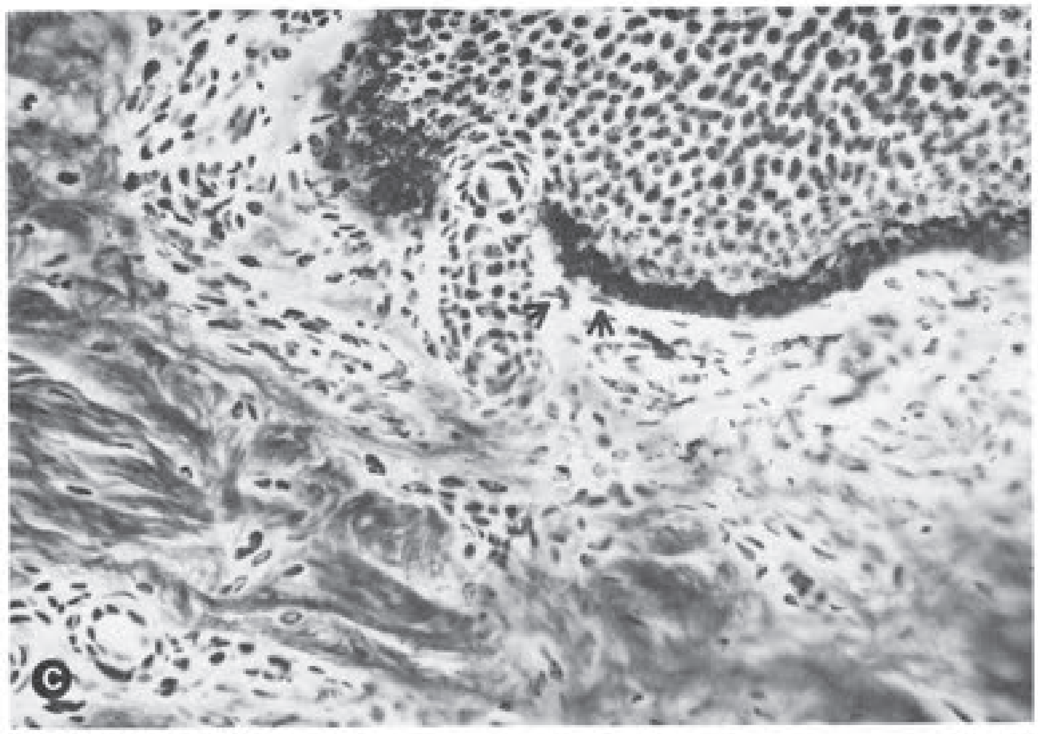

Figure 12.25. *C*, Possible Merkel cell-neurite complex (see legend on PAGE 282)

E. W., a seventeen-year-old, had sustained head trauma from a bike fall at age six. Cerebral hemorrhage resulted in left spastic hemiplegia (Fig. 12.24) and a severe thumb-in-palm deformity that the fingers were forcefully pried apart and an object placed within, there was no ability to recognize the object. Preoperative evaluation of sensibility revealed just perception of moving-touch and the 30- and 256-cps tuning fork stimuli. At surgery, the thumb-in-palm deformity was released and appropriate tendon transfers carried out. A biopsy was done intraoperatively of his middle finger, which demonstrated normal quantity of innervated Meissner corpuscle and Pacinian corpuscle, but few innervated Merkel cell-neurite complexes (Fig. 12.25). Postoperatively he demonstrated increased use of his hand (Fig. 12.26), being able to pick-up and grasp object ts voluntarily, and gradually coming to use the hand for activities of daily living. Evaluation of sensibility at 1 year after surgery demonstrated perception now of constant-touch though there still was no classic two-point discrimination. Moving two-point discrimination was 6 mm and tactile gnosis was recovering.

This demonstrated unequivocally to me that the sensory deprivation *per se* which accompanied spastic hemiplegia can result in a severe loss of functional sensation beyond the true neurophysiologic loss resulting from loss of neural structures. This again represents a potential that may be regained through energetic sensory re-education. This is an entire area awaiting further investigation.

Fingertip Resurfacing

The reconstructed fingertip needs sensory re-education in all cases except local innervated flap reconstruction and healing by secondary intention. In each of these cases, normally innervated distal glabrous skin is the resurfacing agent. However, dorsal cross-finger flaps, palmar flaps, thenar flaps, more distal flaps, and skin grafts of all thickness and from all sources all share in common the resurfacing of the fingertip with noninnervated skin. This skin is reinnervated by the digital nerves. Their regenerating axons enter or fail to enter whatever types of sensory receptors are present in the resurfacing material (including hair follicles). Thus, the fingertip reconstructed with noninnervated grafts or flaps should be viewed as a nerve repair from the standpoint of requiring sensory re-education.

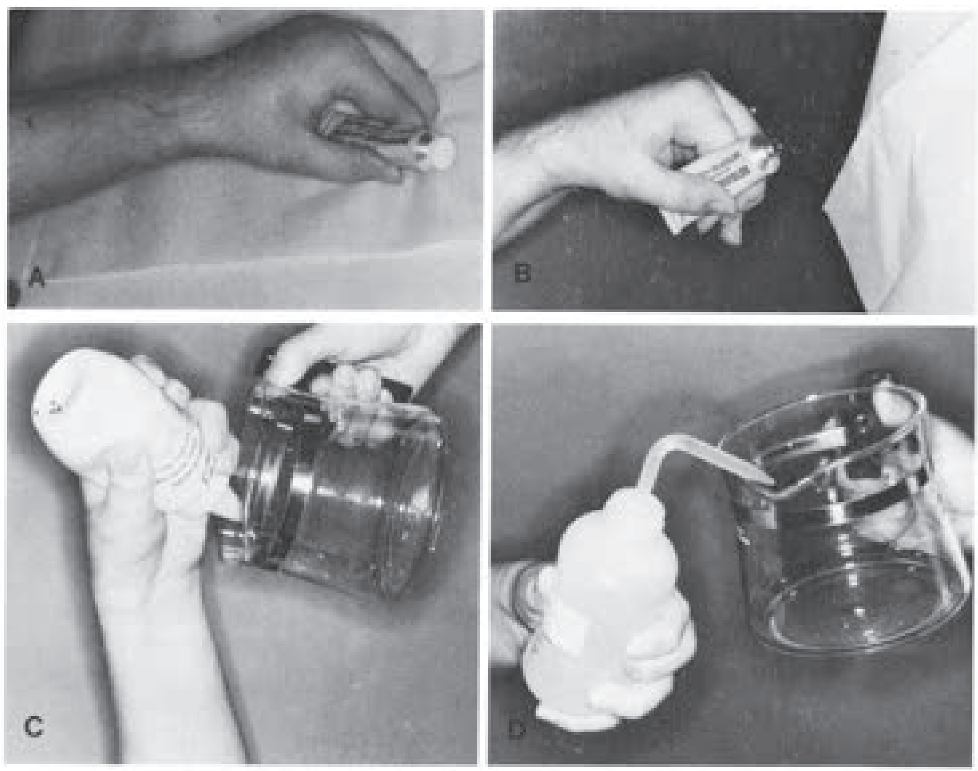

Figure 12.26 Spastic hemiplegia. After 1 year of postoperating rehabilitation, there now was (*A* and *B*) good pinch and (*C* and *D*) some grasp. He used this hand for the activities of daily living. There was now perception of constant-touch, but still no classic two-point discrimination. Moving two-point discrimination was 6 mm and tactile gnosis was recovering.

When resurfacing with a graft is the method to be chosen, favor a full thickness graft from the hypothenar area because this contains the same type of sensory end organs as the fingertip. Resurfacing with nonglabrous skin never permits recovery of tactile gnosis.[92] With a glabrous skin graft, the regenerating end organs have the best chance to reinnervate appropriately skin from the plantar aspect of the foot has the same potential.[93] Many have described the use of hypothenar grafts for fingertip resurfacing,[94-96] but only recently has Thompson[97] provided us with a series in which two-point discrimination is reported. Five of his 10 patients had values between 4 and 6 mm, normal, while the other five ranged from 8 to 12 mm.

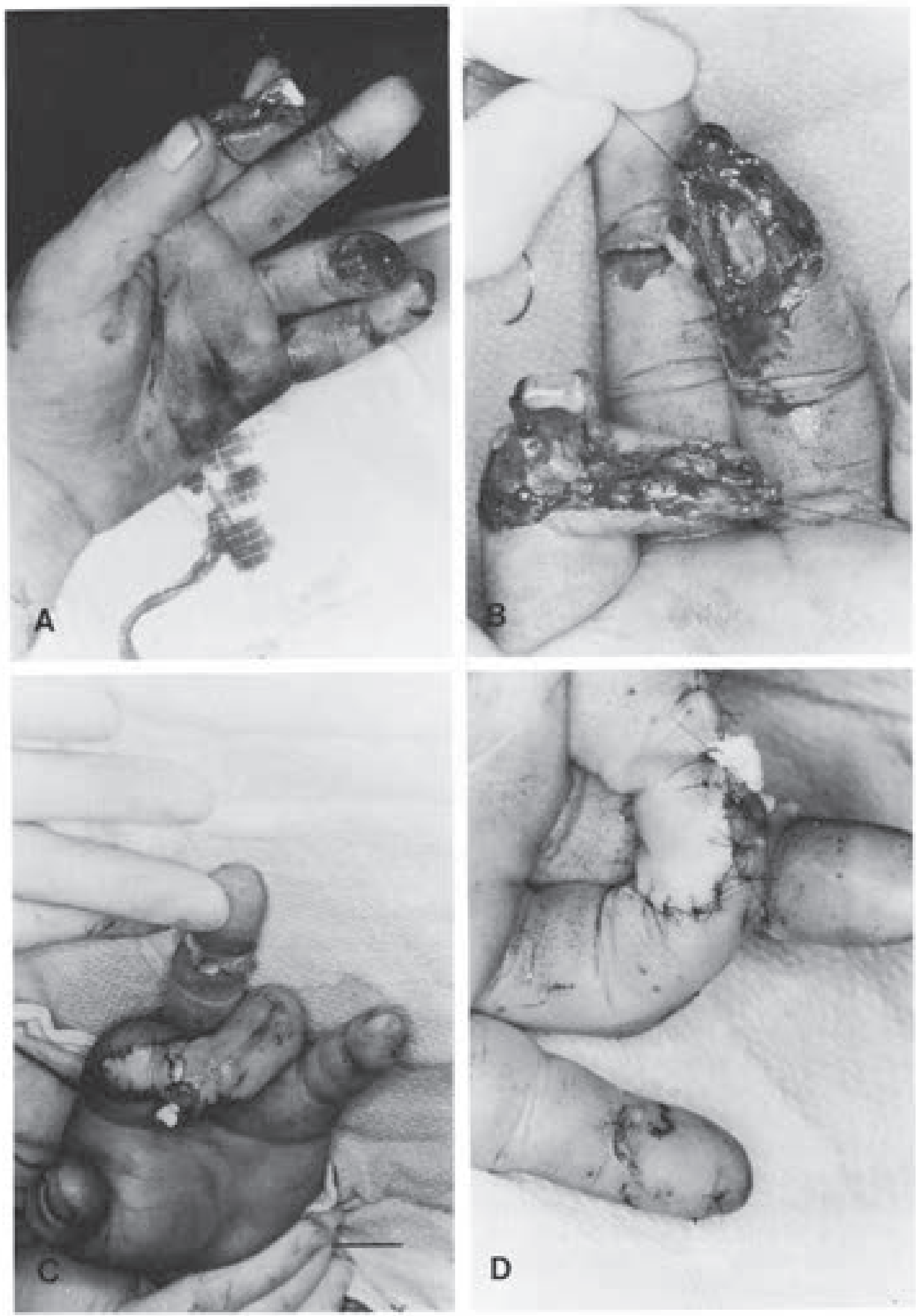

Figure 12.27. Volar cross-finger flap. The trauma setting provided the opportunity *(A)* to use the volar surface of one finger (the index) to resurface and thereby conserve length with normal sensibility in a neighboring digit, the ring *(B)*. After removing middle phalanx from index, the cross-finger flap was inset, and skin from the avulsed index distal phalanx was used as a graft to cover the underside of the flap (*C* and *D*).

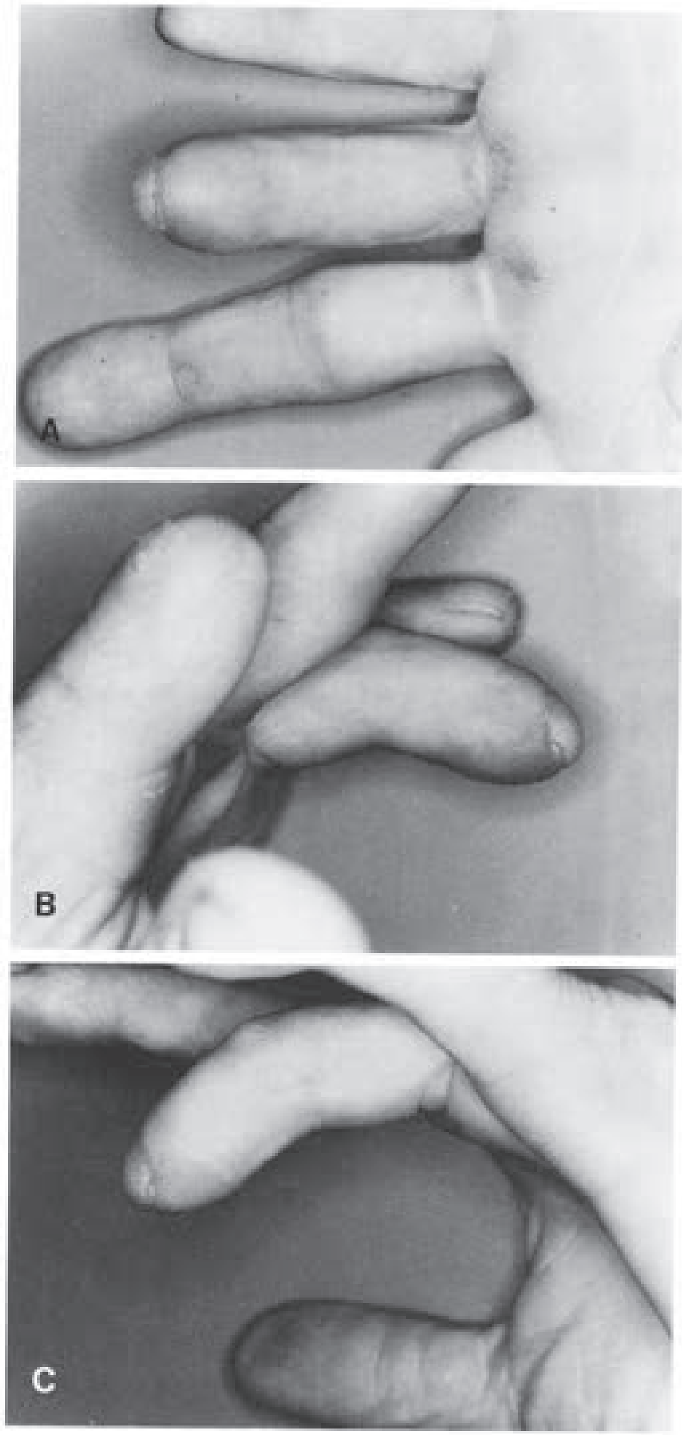

Figure 12.28. Volar cross-finger flap. Follow-up 2 years after surgery. There is now 2 mm of moving two-point discrimination and 3 mm of constant two-point discrimination.

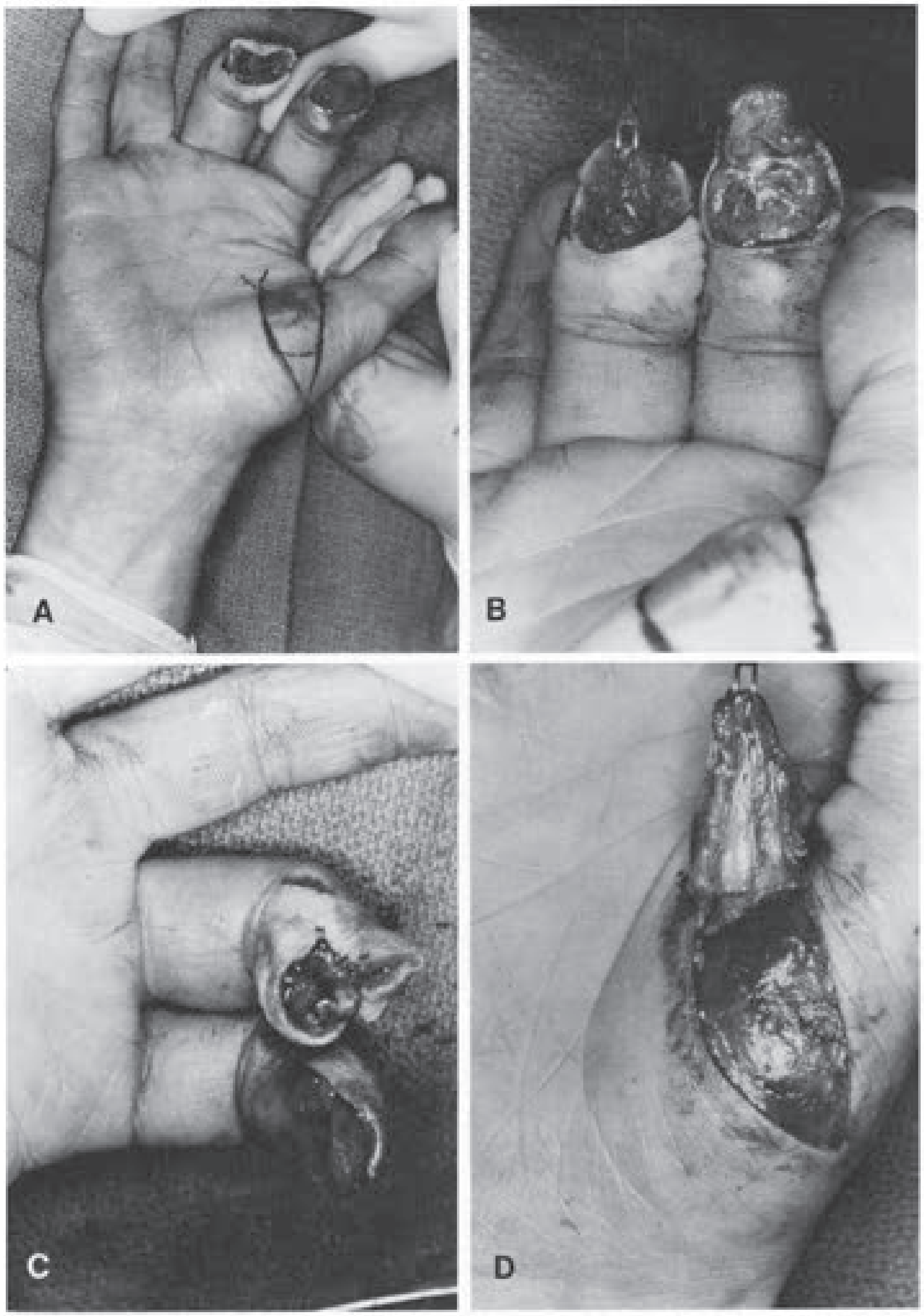

Figure 12.29. Thenar flap: *A* and *B*, Injuries as shown with flap outlined for index fingertip. Note: Triangle marked at end of flap is saved as a graft to cover underside of flap and donor site (see below). *C* and *D*, Middle fingertip will be closed by subcutaneous pedicle flap technique.[117] Index is missing entire volar pulp, with phalanx and nail preserved.

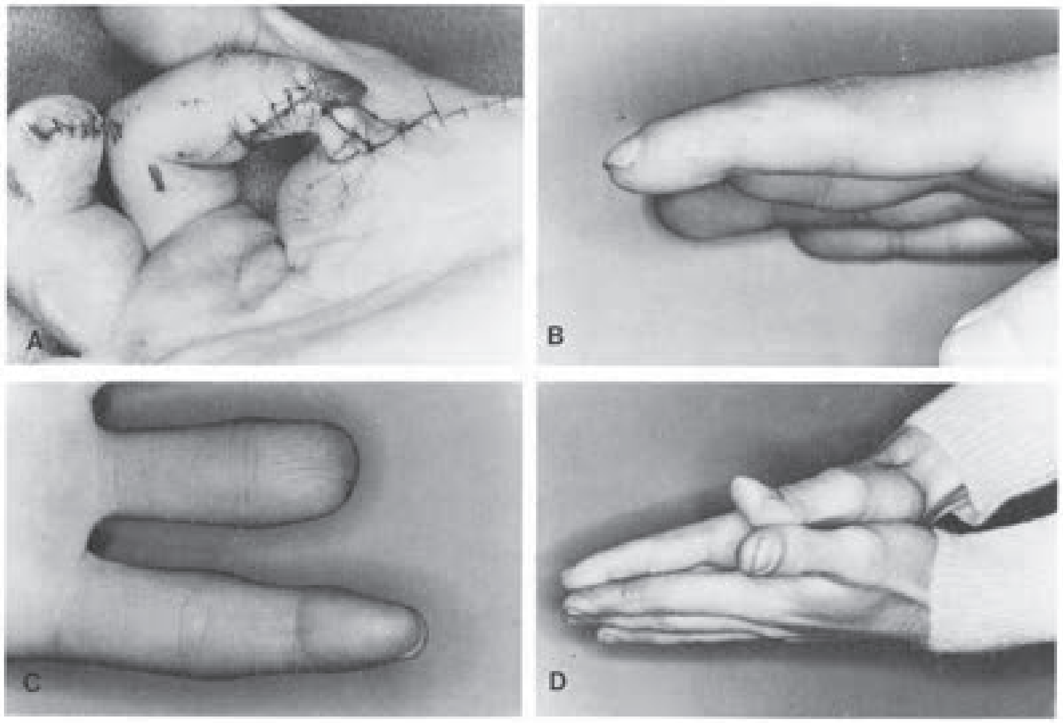

Figure 12.30. Thenar flap: *A*, I prefer to insert the distal tip of the thenar flap, which is, however, the more proximal and radial portion of thenar skin, into the proximal end of the defect. Blood supply is better here also. This approach permits, at inset, retention of a subcutaneous pedicle flap for a modest lengthening of tip or nail support (*B*). End result (*C* and *D*), at 6 months after inset, employing skin and full complement of sensory end-organs, there is 3 mm moving and 4 mm constant two-point after sensory re-education.

The ideal resurfacing material for a fingertip is of course, another fingertip. Sometimes, in trauma with multiple finger injuries, the volar skin from one finger may be grafted to another fingertip. As my preliminary data at the end of Chapter 5 demonstrated, there is the greatest conservation of sensory end organs with a flap, and so the ideal flap is a *volar* cross-finger flap. Again, the trauma setting can provide occasion to use a volar cross finger flap to salvage a neighboring digit (Figs. 12.27 and 12.28). The one flap of this type I have done did recover 2 mm of moving and 3 mm of constant two-point discrimination.

For loss of fingertip pulp where local flap are insufficient, I favor the thenar flap, again because this region has the sensory end organ composition most similar to the distal phalanx. The technique I use places the proximal thenar skin into the proximal finger loss, the distal thenar skin (which has a slightly greater end-organ density) into the fingertip (see Figs. 12.29 and 12.30). Sensory re-education has resulted in recovery of 4 mm classic two-point discrimination and 3 mm moving two-point discrimination in the two cases done with this technique.

For loss of thumb pulp, I favor the volar advancement flap[9, 97-100] which can be "extended" to provide up to 3 cm of distal coverage (Figs. 12.31 and 12.32) with excellent functional sensation.[101]

Innervated Flap Transfers

When a flap is transferred to the fingertip and the flap's nerve is sutured to the volar digital nerve of the recipient finger,[28, 102-104] the need for sensory re-education is similar to that following nerve repair. But when an innervated flap is transferred and its nerve supply remains centrally unchanged, then the need for re-education is different. There has been no nerve repair.

One group of these transfers is the radial-innervated index dorsum to thumb pulp.[105-111] Sensory re-education in this group has two goals: (1) improve the tactile discrimination, as discussed above for the cross-finger flap and (2) correct "false localization." The normal classic two-point discrimination of the skin over the dorsum of the index finger's proximal phalanx is 12 to 15 mm.[112] Among the 34 reported cases,[105-111] there were five[106-107] with classic two-point discrimination of 6 mm or less and eight patients with 8 to 14 mm.[107, 111] Two authors believed that the flap was not good for restoring sensation other than protective.[105-110] Many of these patients had not learned to localize the stimulus to the thumb, but still referred it to the index finger.[105,109,110] One patient made the central adjustment by 10 months and one patient not for 10 years![107] Thus the potential for central reorganization by sensory re-education exists and has been accomplished. Certainly this is an area for improved re-education efforts.

I have used this technique twice. At follow-up evaluation 3 years after surgery, both patients, who had received sensory re-education, had made the central adjustment. One had 5 mm moving two-point discrimination and 10 mm classic two-point discrimination. The other had no two-point discrimination. Both patients were dissatisfied with the scars. At present, this is a flap of last resort for me, and I prefer the extended volar advancement flap[101] (Figs. 12.31 and 12.32)

Neurovascular Island Flap

Four reports of long-term results in patients who have had a neurovascular island flap transferred have made the same general comments.[113-116] Initially, the skin island with digital artery and nerve intact lives and has normal tactile discrimination. Over time, the tested classic two-point discrimination greatly diminishes. Hand function related to this restored sensibility, however, consistently improves. Much theorizing goes on as to why two-point discrimination is lost, but the observed fact is that function has improved. Sensory re-education most certainly must take the credit for this, since the patient's use of the flap allows him to re-educate himself despite the measurable loss in sensation.

Similar to the innervated cross-finger flap, there remains a significant problem with localization of the stimulus. Under slow, consciously directed activity, the ring finger island now on the thumb has its stimuli referred to the thumb. But if the thumb is surprisedly stuck by a pin, the patient believes his ring finger has been hurt! It remains unknown whether further sensory re-education can improve this.

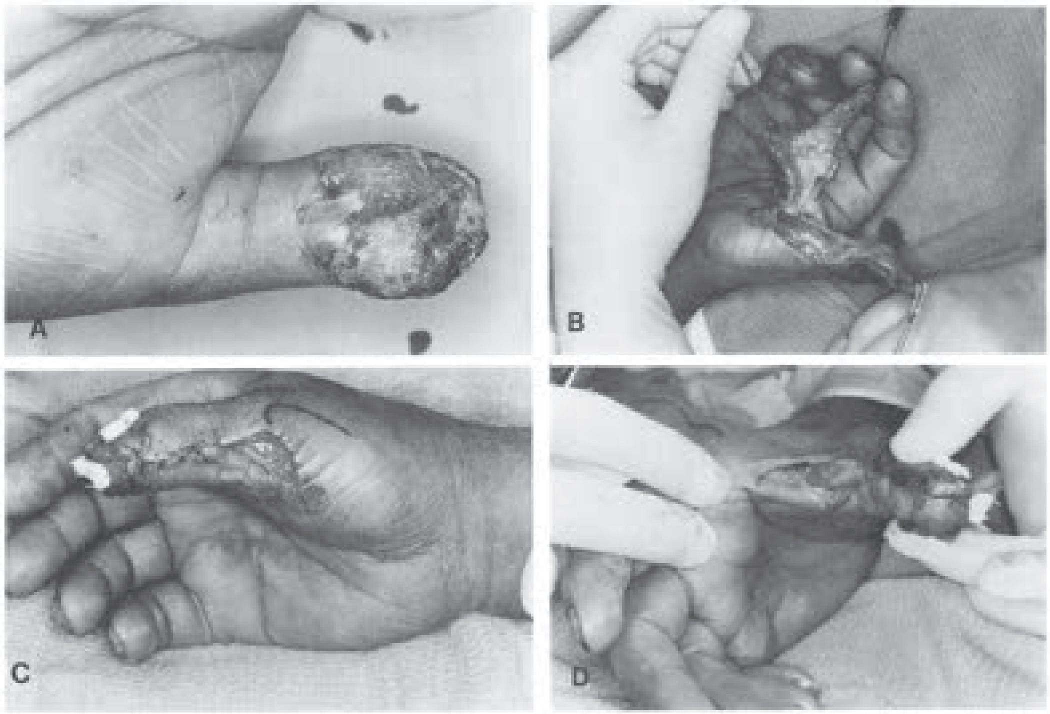

Figure 12.31 Extended volar advancement flap. To resurface extensive thumb pulp losses greater than 1.5 cm (*A*), an innervated extended volar advancement flap is created. By extending the flap proximally, the relative excess of skin over the thenar eminence can be utilized.(*B*) The donor site defects on the radial and ulnar side of the flap are covered with two adjacent rotation flaps, respecting normal skin creases and dorsal versus palmar skin (*C* and *D)*. (Reproduced with permission from A. L. Dellon, in press, 1981.[101])

I have had success with re-educating localization in two patients with these flaps, one followed for 3 years and one followed just 1 year. Two-point discrimination has fallen from normal to 5 mm moving and 15 mm classic in the first case, while remaining normal at 2 mm moving and 3 mm classic so far in the latter case the first patient, in whom discrimination was clearly lost, is a poorly motivated person with a history of multiple self-inflicted wrist injuries, while the second patient is a highly motivated auto mechanic who has since returned to work. The role of sensory re-education in preventing the observed decline in tactile gnosis in neurovascular island flaps remains to be defined.

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