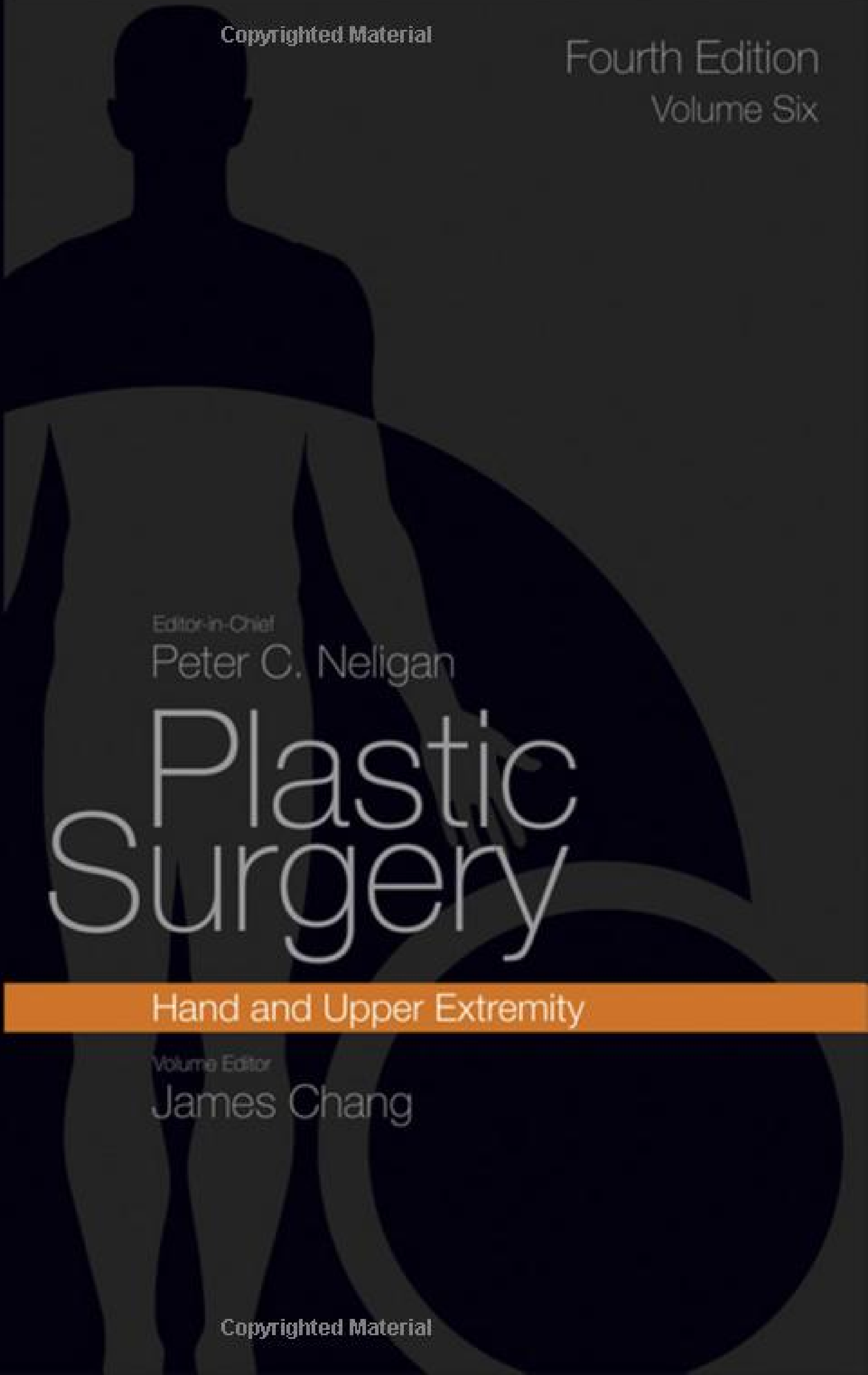
Fourth Edition
Volume Six



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Plastic Surgery

Hand and Upper Extremity

Volume Editor
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Plastic Surgery

Hand and Upper Extremity

Volume Six

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Plastic Surgery

Hand and Upper Extremity

Volume Six

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Video Contents

Volume One:

Chapter 15: Skin graft

15.1: Harvesting a split-thickness skin graft
Dennis P. Orgill

Chapter 34: Robotics in plastic surgery

34.1: Robotic microsurgery
34.2: Robotic rectus abdominis muscle flap harvest
34.3: Trans-oral robotic surgery
34.4: Robotic latissimus dorsi muscle harvest
34.5: Robotic lymphovenous bypass
Jesse C. Selber

Volume Two:

Chapter 6.2: Facelift: Principles of and surgical approaches to facelift

6.2.1: Parotid masseteric fascia
6.2.2: Anterior incision
6.2.3: Posterior incision
6.2.4: Facelift skin flap
6.2.5: Facial fat injection
Richard J. Warren

6.2.6: Anthropometry, cephalometry, and orthognathic surgery
Jonathon S. Jacobs, Jordan M. S. Jacobs, and Daniel I. Taub

Chapter 6.3: Facelift: Platysma-SMAS plication

6.3.1: Platysma-SMAS plication
Dai M. Davies and Miles G. Berry

Chapter 6.4: Facelift: Facial rejuvenation with loop sutures – the MACS lift and its derivatives

6.4.1: Loop sutures MACS facelift
Patrick L. Tonnard
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Chapter 6.7: Facelift: SMAS with skin attached – the "high SMAS" technique

6.7.1: The high SMAS technique with septal reset
Fritz E. Barton Jr.
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Chapter 6.8: Facelift: Subperiosteal midface lift

6.8.1: Subperiosteal midface lift: Endoscopic temporo-midface
Oscar M. Ramirez

Chapter 9: Blepharoplasty

9.1: Periorbital rejuvenation
Julius Few Jr. and Marco Ellis
© Julius Few Jr.

Chapter 11: Asian facial cosmetic surgery

1.1: Medial epicanthoplasty
11.2: Eyelidplasty: Non-incisional method
11.3: Rhinoplasty
11.4: Subclinical ptosis correction (total)
11.5: Secondary rhinoplasty: Septal extension graft and costal cartilage strut fixed with K-wire
Kyung S. Koh, Jong Woo Choi, and Clyde H. Ishii

Chapter 12: Neck rejuvenation

12.1: Anterior lipectomy
James E. Zins, Colin M. Morrison, and C. J. Langevin

Chapter 13: Structural fat grafting

13.1: Structural fat grafting of the face
Sydney R. Coleman and Alesia P. Saboeiro

Chapter 14: Skeletal augmentation

14.1: Chin implant
Michael J. Yarumchuk
© Mesa J, Havlik R, Mackay D, Buchman S, Losee J, eds. Atlas of Operative Craniofacial Surgery, CRC Press, 2019.

14.2: Mandibular angle implant
14.3: Midface skeletal augmentation and rejuvenation
Michael J. Yarumchuk
© Michael J. Yaremchuk

Chapter 16: Open technique rhinoplasty

16.1: Open technique rhinoplasty
Allen L. Van Beek

Chapter 20: Otoplasty and ear reduction

20.1: Setback otoplasty
Leila Kasrai

Chapter 23: Abdominoplasty procedures

23.1: Abdominoplasty
Dirk F. Richter and Alexander Stoff

Chapter 24: Lipoabdominoplasty

24.1: Lipoabdominoplasty (including secondary lipo)
Osvaldo Saldanha, Sérgio Fernando Dantas de Azevedo, Osvaldo Ribeiro Saldanha Filho, Cristianna Bonnetto Saldanha, and Luis Humberto Uribe Morelli

Chapter 26.2: Buttock augmentation: Buttock augmentation with implants

26.2.1: Buttock augmentation
Terrence W. Bruner, Jose Abel De la Peña Salcedo, Constantino G. Mendieta, and Thomas L. Roberts III

Chapter 27: Upper limb contouring

27.1: Brachioplasty
27.2: Upper limb contouring
Joseph F. Capella, Matthew J. Trovato, and Scott Woehrle

Chapter 28: Post-bariatric reconstruction

28.1: Post-bariatric reconstruction – bodylift procedure
J. Peter Rubin and Jonathan W. Toy
© J. Peter Rubin

Volume Three:

Chapter 6: Aesthetic nasal reconstruction

6.1: The three-stage folded forehead flap for cover and lining
6.2: First-stage transfer and intermediate operation
Frederick J. Menick

Chapter 7: Auricular construction

7.1: Total auricular construction
Akira Yamada

Chapter 8: Acquired cranial and facial bone deformities

8.1: Removal of venous malformation enveloping intraconal optic nerve
Renee M. Burke, Robert J. Morin, and S. Anthony Wolfe

Chapter 13: Facial paralysis

13.1: Facial paralysis
Eyal Gur

13.2: Facial paralysis
13.3: Cross facial nerve graft
13.4: Gracilis harvest
Peter C. Neligan

Chapter 14: Pharyngeal and esophageal reconstruction

14.1: Reconstruction of pharyngoesophageal defects with the anterolateral thigh flap
Peirong Yu

Chapter 15: Tumors of the facial skeleton: Fibrous dysplasia

15.1: Surgical approaches to the facial skeleton
Yu-Ray Chen, You-Wei Cheong, and Alberto Córdova-Aguilar

Chapter 17: Local flaps for facial coverage

17.1: Facial artery perforator flap
17.2: Local flaps for facial coverage
Peter C. Neligan

Chapter 21.2: Rotation advancement cheiloplasty

21.2.1: Repair of unilateral cleft lip
Philip Kuo-Ting Chen, M. Samuel Noordhoff, Frank Chun-Shin, Chang, and Fuan Chiang Chan

21.2.2: Unilateral cleft lip repair – anatomic subunit approximation technique
David M. Fisher

Chapter 24: Alveolar clefts

24.1: Unilateral cleft alveolar bone graft
24.2: Mobilized premaxilla after vomer osteotomy prior to setback and splint application
Richard A. Hopper and Gerhard S. Mundinger

Chapter 26: Velopharyngeal dysfunction

26.1: Velopharyngeal incompetence – 1
26.2: Velopharyngeal incompetence – 2
26.3: Velopharyngeal incompetence – 3
Richard E. Kirschner and Adriane L. Baylis

Chapter 27: Secondary deformities of the cleft lip, nose, and palate

27.1: Abbé flap
27.2: Alveolar bone grafting
27.3: Complete takedown
27.4: Definitive rhinoplasty
Evan M. Feldman, John C. Koshy, Larry H. Hollier Jr., and Samuel Stal

27.5: Thick lip and buccal sulcus deformities
Evan M. Feldman and John C. Koshy

Chapter 36: Pierre Robin Sequence

36.1: Mandibular distraction
Arun K. Gosain and Chad A. Purnell

Chapter 39: Vascular anomalies

39.1: Lip hemangioma
Arin K. Greene

Chapter 43: Reconstruction of urogenital defects: Congenital

43.1: First-stage hypospadias repair with free inner preputial graft
43.2: Second-stage hypospadias repair with tunica vaginalis flap
Mohan S. Gundeti and Michael C. Large

Volume Four:

Chapter 2: Management of lower extremity trauma

2.1: Anterolateral thigh flap harvest
Michel Saint-Cyr

Chapter 3: Lymphatic reconstruction of the extremities

3.1: End-to-side lymphovenous bypass technique
© Cheng M-H, Chang D, Patel K. Principles and Practice of Lymphedema Surgery, Elsevier; 2015.

3.2: Recipient site preparation for vascularized lymph node transfer – axilla
© Cheng M-H, Chang D, Patel K. Principles and Practice of Lymphedema Surgery, Elsevier; 2015.

3.3: Indocyanine green lymphography
David W. Chang

3.4: Charles procedure
Peter C. Neligan

Chapter 6: Diagnosis and treatment of painful neuroma and nerve compression in the lower extremity

6.1: Diagnosis and treatment of painful neuroma and of nerve compression in the lower extremity 1
6.2: Diagnosis and treatment of painful neuroma and of nerve compression in the lower extremity 2

6.3: Diagnosis and treatment of painful neuroma and of nerve compression in the lower extremity 3
A. Lee Dellon

Chapter 7: Skeletal reconstruction

7.1: Medial femoral condyle/medial geniculate artery osteocutaneous free flap dissection for scaphoid nonunion
Stephen J. Kovach III and L. Scott Levin

Chapter 10: Reconstruction of the chest

10.1: Sternal rigid fixation
David H. Song and Michelle C. Roughton

Chapter 12: Abdominal wall reconstruction

12.1: Component separation innovation
Peter C. Neligan

Chapter 13: Reconstruction of male genital defects

13.1: Complete and partial penile reconstruction
Stan Monstrey, Peter Ceulemans, Nathalie Roche, Philippe Houtmeyers, Nicolas Lumen, and Piet Hoebeke

Volume Five:

Chapter 6: Mastopexy options and techniques

6.1: Circumareolar mastopexy
Kenneth C. Shestak

Chapter 7: One- and two-stage considerations for augmentation mastopexy

7.1: Preoperative markings for a single-stage augmentation mastopexy
W. Grant Stevens

Chapter 10: Reduction mammaplasty with short scar techniques

10.1: SPAIR technique
Dennis C. Hammond

Chapter 11: Gynecomastia surgery

11.1: Ultrasound-assisted liposuction
Charles M. Malata

Chapter 15: One- and two-stage prosthetic reconstruction in nipple-sparing mastectomy

15.1: Pectoralis muscle elevation
15.2: Acellular dermal matrix
15.3: Sizer
Amy S. Colwell

Chapter 16: Skin-sparing mastectomy: Planned two-stage and direct-to-implant breast reconstruction

16.1: Mastectomy and expander insertion: First stage
16.2: Mastectomy and expander insertion: Second stage
Maurizio B. Nava, Giuseppe Catanuto, Angela Pennati, Valentina Visintini Cividin, and Andrea Spano

Chapter 19: Latissimus dorsi flap breast reconstruction

19.1: Latissimus dorsi flap technique
Scott L. Spear†

19.2: Markings
19.3: Intraoperative skin paddles
19.4: Tendon division
19.5: Transposition and skin paddles
19.6: Inset and better skin paddle explanation
Neil A. Fine and Michael S. Gart

Chapter 20.2: The deep inferior epigastric artery perforator (DIEAP) flap

20.2.1: The Deep Inferior Epigastric Artery Perforator (DIEAP) flap breast reconstruction
Phillip N. Blondeel and Robert J. Allen, Sr

Chapter 21.2: Gluteal free flaps for breast reconstruction

21.2.1: Superior Gluteal Artery Perforator (SGAP) flap
21.2.2: Inferior Gluteal Artery Perforator (IGAP) flap
Peter C. Neligan

Chapter 21.3: Medial thigh flaps for breast reconstruction

21.3.1: Transverse Upper Gracilis (TUG) flap 1
Peter C. Neligan

21.3.2: Transverse Upper Gracilis (TUG) flap 2
Venkat V. Ramakrishnan

Chapter 23.2: Partial breast reconstruction using reduction and mastopexy techniques

23.2.1: Partial breast reconstruction using reduction mammoplasty
Maurice Y. Nahabedian

23.2.2: Partial breast reconstruction with a latissimus dorsi flap
Neil A. Fine

23.2.3: Partial breast reconstruction with a pedicle TRAM
Maurice Y. Nahabedian

Volume Six:

Chapter 1: Anatomy and biomechanics of the hand

1.1: The extensor tendon compartments
1.2: The contribution of the interosseous and lumbrical muscles to the lateral bands
1.3: Extrinsic flexors and surrounding vasculonervous elements, from superficial to deep
1.4: The lumbrical plus deformity
1.5: The sensory and motor branches of the median nerve in the hand
James Chang, Vincent R. Hentz, Robert A. Chase, and Anais Legrand

Chapter 2: Examination of the upper extremity

2.1: Flexor profundus test in a normal long finger
2.2: Flexor sublimis test in a normal long finger
2.3: Extensor pollicis longus test in a normal person
2.4: Test for the Extensor Digitorum Communis (EDC) muscle in a normal hand
2.5: Test for assessing thenar muscle function
2.6: The "cross fingers" sign
2.7: Static Two-Point Discrimination Test (s-2PD Test)
2.8: Moving 2PD Test (m-2PD Test) performed on the radial or ulnar aspect of the finger

2.9: Semmes–Weinstein monofilament test: The patient should sense the pressure produced by bending the filament
2.10: Allen's test in a normal person
2.11: Digital Allen's test
2.12: Scaphoid shift test
2.13: Dynamic tenodesis effect in a normal hand
2.14: The milking test of the fingers and thumb in a normal hand
2.15: Eichhoff test
2.16: Adson test
2.17: Roos test
Ryosuke Kakinoki

Chapter 3: Diagnostic imaging of the hand and wrist

3.1: Scaphoid lunate dislocation
Alphonsus K. Chong and David M. K. Tan

3.2: Right wrist positive midcarpal catch up clunk
Alphonsus K. Chong

Chapter 4: Anesthesia for upper extremity surgery

4.1: Supraclavicular block
Subhro K. Sen

Chapter 5: Principles of internal fixation as applied to the hand and wrist

5.1: Dynamic compression plating and lag screw technique
Christopher Cox

5.2: Headless compression screw
5.3: Locking vs. non-locking plates
Jeffrey Yao and Jason R. Kang

Chapter 7: Hand fractures and joint injuries

7.1: Bennett reduction
7.2: Hemi-Hamate arthroplasty
Warren C. Hammert

Chapter 9: Flexor tendon injury and reconstruction

9.1: Zone II flexor tendon repair
9.2: Incision and feed tendon forward
9.3: Distal tendon exposure
9.4: Six-strand M-tang repair
9.5: Extension–flexion test – wide awake
Jin Bo Tang

Chapter 10: Extensor tendon injuries

10.1: Sagittal band reconstruction
10.2: Setting the tension in extensor indicis transfer
Kai Megerle

Chapter 11: Replantation and revascularization

11.1: Hand replantation
James Chang

Chapter 12: Reconstructive surgery of the mutilated hand

12.1: Debridement technique
James Chang

Chapter 13: Thumb reconstruction: Non-microsurgical techniques

13.1: Osteoplastic thumb reconstruction
13.2: First Dorsal Metacarpal Artery (FDMA) flap
Jeffrey B. Friedrich

Chapter 14: Thumb reconstruction: Microsurgical techniques

14.1: Trimmed great toe
14.2: Second toe for index finger
14.3: Combined second and third toe for metacarpal hand
Nidal F. Al Deek

Chapter 19: Rheumatologic conditions of the hand and wrist

19.1: Extensor tendon rupture and end–side tendon transfer
James Chang

19.2: Silicone metacarpophalangeal arthroplasty
Kevin C. Chung and Evan Kowalski

Chapter 20: Osteoarthritis in the hand and wrist

20.1: Ligament reconstruction tendon interposition arthroplasty of the thumb carpometacarpal joint
James W. Fletcher

Chapter 21: The stiff hand and the spastic hand

21.1: Flexor pronator slide
David T. Netscher

Chapter 22: Ischemia of the hand

22.1: Radial artery sympathectomy
Hee Chang Ahn and Neil F. Jones

22.2: Interposition arterial graft and sympathectomy
Hee Chang Ahn

Chapter 24: Nerve entrapment syndromes

24.1: The manual muscle testing algorithm
24.2: Scratch collapse test – carpal tunnel
Elisabet Hagert

24.3: Injection technique for carpal tunnel surgery
24.4: Wide awake carpal tunnel surgery
Donald Lalonde

24.5: Clinical exam and surgical technique – lacertus syndrome
Elisabet Hagert

24.6: Injection technique for cubital tunnel surgery
24.7: Wide awake cubital tunnel surgery
Donald Lalonde

24.8: Clinical exam and surgical technique – radial tunnel syndrome
24.9: Clinical exam and surgical technique – lateral intermuscular syndrome
24.10: Clinical exam and surgical technique – axillary nerve entrapment
Elisabet Hagert

24.11: Carpal tunnel and cubital tunnel releases in the same patient in one procedure with field sterility: Part 1 – local anesthetic injection for carpal tunnel
24.12: Carpal tunnel and cubital tunnel releases in the same patient in one procedure with field sterility: Part 2 – local anesthetic injection for cubital tunnel
Donald Lalonde and Michael Bezuhly

Chapter 25: Congenital hand I: Embryology, classification, and principles

25.1: Pediatric trigger thumb release
James Chang

Chapter 27: Congenital hand III: Thumb hypoplasia

27.1: Thumb hypoplasia
Joseph Upton III and Amir Taghinia

Chapter 30: Growth considerations in pediatric upper extremity trauma and reconstruction

30.1: Epiphyseal transplant harvesting technique
Marco Innocenti and Carla Baldrighi

Chapter 31: Vascular anomalies of the upper extremity

31.1: Excision of venous malformation
Joseph Upton III and Amir Taghinia

Chapter 32: Peripheral nerve injuries of the upper extremity

32.1: Suture repair of the cut digital nerve
32.2: Suture repair of the median nerve
Simon Farnebo and Johan Thorfinn

Chapter 35: Free-functioning muscle transfer in the upper extremity

35.1: Gracilis functional muscle harvest
Gregory H. Borschel

Chapter 36: Brachial plexus injuries: Adult and pediatric

36.1: Pediatric: shoulder correct and biceps-to-triceps transfer with preserving intact brachialis
36.2: Adult: results of one-stage surgery for C5 rupture, C6–T1 root avulsion 10 years after
36.3: Nerve transfer results 1
36.4: Nerve transfer results 2
36.5: Nerve transfer results 3
36.6: Nerve transfer results 4
36.7: Nerve transfer results 5
David Chwei-Chin Chuang

Chapter 37: Restoration of upper extremity function in tetraplegia

37.1: The single-stage grip and release procedure
37.2: Postoperative results after single-stage grip release procedure in OCu3–5 patients
Carina Reinholdt and Catherine Curtin

Chapter 38: Upper extremity vascularized composite allotransplantation

38.1: Upper extremity composite tissue allotransplantation
W. P. Andrew Lee and Vijay S. Gorantla

Chapter 39: Hand therapy

39.1: Goniometric measurement
39.2: Threshold testing
Christine B. Novak and Rebecca L. Neiduski

Lecture Video Contents

Volume One:

Chapter 1: Plastic surgery and innovation in medicine

Plastic surgery and innovation in medicine
Peter C. Neligan

Chapter 7: Digital imaging in plastic surgery

Digital imaging in plastic surgery
Daniel Z. Liu

Chapter 15: Skin graft

Skin graft
Peter C. Neligan

Chapter 19: Repair and grafting of peripheral nerve

Nerve injury and repair
Kirsty Usher Boyd, Andrew Yee, and Susan E. Mackinnon

Chapter 20: Reconstructive fat grafting

Reconstructive fat grafting
J. Peter Rubin

Chapter 21: Vascular territories

Vascular territories
Steven F. Morris

Chapter 22: Flap classification and applications

Flap classification and applications
Joon Pio Hong

Chapter 23: Flap pathophysiology and pharmacology

Flap pathophysiology and pharmacology
Cho Y. Pang and Peter C. Neligan

Chapter 24: Principles and techniques of microvascular surgery

Principles and techniques of microvascular surgery
Fu-Chan Wei, Nidal F. Al Deek, and Sherilyn Keng Lin Tay

Chapter 25: Principles and applications of tissue expansion

Principles and applications of tissue expansion
Ivo Alexander Pestana, Louis C. Argenta, and Malcolm W. Marks

Chapter 26: Principles of radiation

Therapeutic radiation: principles, effects, and complications
Gabrielle M. Kane

Chapter 28: Benign and malignant nonmelanocytic tumors of the skin and soft tissue

Benign and malignant nonmelanocytic tumors of the skin and soft tissue
Rei Ogawa

Chapter 31: Facial prosthetics in plastic surgery

Facial prosthetics in plastic surgery
Gordon H. Wilkes

Volume Two:

Chapter 4: Skincare and nonsurgical skin rejuvenation

Skincare and nonsurgical skin rejuvenation
Leslie Baumann and Edmund Weisberg

Chapter 5.2: Injectables and resurfacing techniques: Soft-tissue fillers

Soft-tissue fillers
Trevor M. Born, Lisa E. Airan, and Daniel Suissa

Chapter 5.3: Injectables and resurfacing techniques: Botulinum toxin (BoNT-A)

Botulinum toxin
Michael A. C. Kane

Chapter 5.4: Injectables and resurfacing techniques: Laser resurfacing

Laser resurfacing
Steven R. Cohen, Ahmad N. Saad, Tracy Leong, and E. Victor Ross

Chapter 5.5: Injectables and resurfacing techniques: Chemical peels

Chemical peels
Suzan Obagi

Chapter 6.1: Facelift: Facial anatomy and aging

Anatomy of the aging face
Bryan Mendelson and Chin-Ho Wong

Chapter 6.2: Facelift: Principles of and surgical approaches to facelift

Principles of and surgical approaches to facelift
Richard J. Warren

Chapter 6.3: Facelift: Platysma-SMAS plication

Platysma-SMAS plication
Miles G. Berry

Chapter 6.4: Facelift: Facial rejuvenation with loop sutures – the MACS lift and its derivatives

Facial rejuvenation with loop sutures – the MACS lift and its derivatives

Mark Laurence Jewell

Chapter 6.5: Facelift: Lateral SMASectomy facelift

Lateral SMASectomy facelift

Daniel C. Baker and Steven M. Levine

Chapter 6.6: Facelift: The extended SMAS technique in facial rejuvenation

The extended SMAS technique in facelift

James M. Stuzin

Chapter 6.7: Facelift: SMAS with skin attached – the "high SMAS" technique

SMAS with skin attached – the high SMAS technique

Fritz E. Barton Jr.

Chapter 6.8: Facelift: Subperiosteal midface lift

Subperiosteal midface lift

Alan Yan and Michael J. Yaremchuk

Chapter 6.9: Facelift: Male facelift

Male facelift

Timothy J. Marten and Dino Elyassnia

Chapter 6.10: Facelift: Secondary deformities and the secondary facelift

Secondary deformities and the secondary facelift

Timothy J. Marten and Dino Elyassnia

Chapter 7: Forehead rejuvenation

Forehead rejuvenation

Richard J. Warren

Chapter 8: Endoscopic brow lifting

Endoscopic brow lift

Renato Saltz and Alyssa Lolofie

Chapter 9: Blepharoplasty

Blepharoplasty

Julius Few Jr. and Marco Ellis

Chapter 11: Asian facial cosmetic surgery

Asian facial cosmetic surgery

Clyde H. Ishii

Chapter 12: Neck rejuvenation

Neck rejuvenation

James E. Zins, Joshua T. Waltzman, and Rafael A. Couto

Chapter 13: Structural fat grafting

Structural fat grafting

Sydney R. Coleman and Alesia P. Saboeiro

Chapter 15: Nasal analysis and anatomy

Nasal analysis and anatomy

Rod J. Rohrich

Chapter 19: Secondary rhinoplasty

Secondary rhinoplasty

Ronald P. Gruber, Simeon H. Wall Jr., David L. Kaufman, and David M. Kahn

Chapter 21: Hair restoration

Hair restoration

Jack Fisher

Chapter 22.1: Liposuction: A comprehensive review of techniques and safety

Liposuction

Phillip J. Stephan, Phillip Dauwe, and Jeffrey Kenkel

Chapter 22.2: Correction of liposuction deformities with the SAFE liposuction technique

SAFE liposuction technique

Simeon H. Wall Jr. and Paul N. Afrooz

Chapter 23: Abdominoplasty procedures

Abdominoplasty

Dirk F. Richter and Nina Schwaiger

Chapter 25.2: Circumferential approaches to truncal contouring: Belt lipectomy

Belt lipectomy

Al S. Aly, Khalid Al-Zahrani, and Albert Cram

Chapter 25.3: Circumferential approaches to truncal contouring: The lower lipo-bodylift

Circumferential lower bodylift

Dirk F. Richter and Nina Schwaiger

Chapter 25.4: Circumferential approaches to truncal contouring: Autologous buttocks augmentation with purse string gluteoplasty

Purse string gluteoplasty

Joseph P. Hunstad and Nicholas A. Flugstad

Chapter 25.5: Circumferential approaches to truncal contouring: Lower bodylift with autologous gluteal flaps for augmentation and preservation of gluteal contour

Lower bodylift with gluteal flaps

Robert F. Centeno and Jazmina M. Gonzalez

Chapter 26.3: Buttock augmentation: Buttock shaping with fat grafting and liposuction

Buttock shaping with fat grafting and liposuction

Constantino G. Mendieta, Thomas L. Roberts III, and Terrence W. Bruner

Chapter 27: Upper limb contouring

Upper limb contouring

Joseph F. Capella, Matthew J. Trovato, and Scott Woehrle

Chapter 30: Aesthetic genital surgery

Aesthetic genital surgery

Gary J. Alter

Volume Three:

Chapter 10.3: Midface reconstruction: The M. D. Anderson approach

Midfacial reconstruction: The M. D. Anderson approach
Matthew M. Hanasono and Roman Skoracki

Chapter 12: Lip reconstruction

Lip reconstruction
Peter C. Neligan and Lawrence J. Gottlieb

Chapter 14: Pharyngeal and esophageal reconstruction

Pharyngoesophageal reconstruction
Peirong Yu

Chapter 15: Tumors of the facial skeleton: Fibrous dysplasia

Fibrous dysplasia
Alberto Córdova-Aguilar and Yu-Ray Chen

Chapter 17: Local flaps for facial coverage

Local flaps for facial coverage
David W. Mathes

Chapter 19: Facial transplant

Facial transplant
Michael Sosin and Eduardo D. Rodriguez

Chapter 32: Nonsyndromic craniosynostosis

Nonsyndromic craniosynostosis
Patrick A. Gerety, Jesse A. Taylor, and Scott P. Bartlett

Chapter 36: Pierre Robin Sequence

Pierre Robin sequence
Chad A. Purnell and Arun K. Gosain

Chapter 39: Vascular anomalies

Vascular anomalies
Arin K. Greene and John B. Mulliken

Volume Four:

Chapter 2: Management of lower extremity trauma

Management of lower extremity trauma
Yoo Joon Sur, Shannon M. Colohan, and Michel Saint-Cyr

Chapter 15: Surgery for gender identity disorder

Surgery for gender identity disorder
Loren S. Schechter

Chapter 16: Pressure sores

Pressure sores
Robert Kwon, Juan L. Rendon, and Jeffrey E. Janis

Chapter 17: Perineal reconstruction

Perineal reconstruction
Hakim K. Said and Otway Louie

Volume Five:

Chapter 5: Breast augmentation with autologous fat grafting

Breast augmentation with autologous fat grafting
E. Delay

Chapter 6: Mastopexy options and techniques

Mastopexy
Robert Cohen

Chapter 9: Reduction mammaplasty with inverted-T techniques

Reduction mammaplasty with inverted-T techniques
Maurice Y. Nahabedian

Chapter 15: One- and two-stage prosthetic reconstruction in nipple-sparing mastectomy

Prosthetic reconstruction in nipple-sparing mastectomy
Amy S. Colwell

Chapter 20.1: Abdominally based free flaps: Introduction

Abdominally-based autologous breast reconstruction
Maurice Y. Nahabedian, Phillip N. Blondeel, and David H. Song

Chapter 20.2: The deep inferior epigastric artery perforator (DIEAP) flap

Abdominally-based autologous breast reconstruction
Maurice Y. Nahabedian, Phillip N. Blondeel, and David H. Song

Chapter 20.3: The superficial inferior epigastric artery (SIEA) flap

Abdominally-based autologous breast reconstruction
Maurice Y. Nahabedian, Phillip N. Blondeel, and David H. Song

Chapter 20.4: The free TRAM flap

Abdominally-based autologous breast reconstruction
Maurice Y. Nahabedian, Phillip N. Blondeel, and David H. Song

Chapter 25: Radiation therapy considerations in the setting of breast reconstruction

Radiation therapy in breast reconstruction
Steven Kronowitz

Volume Six:

Chapter 7: Hand fractures and joint injuries

Hand fractures and joint injuries
Joseph S. Khouri and Warren C. Hammert

Chapter 13: Thumb reconstruction: Non-microsurgical techniques

Thumb reconstruction
Nicholas B. Vedder and Jeffrey B. Friedrich

Chapter 21: The stiff hand and the spastic hand

The stiff hand
David T. Netscher, Kenneth W. Donohue, and Dang T. Pham

Chapter 24: Nerve entrapment syndromes

Tips and pearls on common nerve compressions
Elisabet Hagert and Donald Lalonde

Chapter 30: Growth considerations in pediatric upper extremity trauma and reconstruction

Growth considerations in pediatric upper extremity trauma and reconstruction
Marco Innocenti and Carla Baldrighi

Chapter 33: Nerve transfers

Nerve injury and repair
Kirsty Usher Boyd, Andrew Yee, and Susan E. Mackinnon

Chapter 37: Restoration of upper extremity function in tetraplegia

Restoration of upper extremity function in tetraplegia
Carina Reinholdt and Catherine Curtin

Preface to the Fourth Edition

When I wrote the preface to the 3rd edition of this book, I remarked how honored and unexpectedly surprised I was to be the Editor of this great series. This time 'round, I'm equally grateful to carry this series forward. When Elsevier called me and suggested it was time to prepare the 4th edition, my initial reaction was that this was way too soon. What could possibly have changed in Plastic Surgery since the 3rd edition was launched in 2012? As it transpires, there have been many developments and I hope we have captured them in this edition.

We have an extraordinary specialty. A recent article by Chadra, Agarwal and Agarwal entitled "Redefining Plastic Surgery" appeared in *Plastic and Reconstructive Surgery—Global Open*. In it they gave the following definition: "Plastic surgery is a specialized branch of surgery, which deals with deformities, defects and abnormalities of the organs of perception, organs of action and the organs guarding the external passages, besides innovation, implantation, replantation and transplantation of tissues, and aims at restoring and improving their form, function and the esthetic appearances." This is an all-encompassing but very apt definition and captures the enormous scope of the specialty.[1]

In the 3rd edition, I introduced volume editors for each of the areas of the specialty because the truth is that one person can no longer be an expert in all areas of this diverse specialty, and I'm certainly not. I think this worked well because the volume editors not only had the expertise to present their area of subspecialty in the best light, but they were tuned in to what was new and who was doing it. We have continued this model in this new edition. Four of the seven volume editors from the previous edition have again helped to bring the latest and the best to this edition: Drs Gurtner, Song, Rodriguez, Losee, and Chang have revised and updated their respective volumes with some chapters remaining, some extensively revised, some added, and some deleted. Dr. Peter Rubin has replaced Dr. Rick Warren to compile the Aesthetic volume (Vol. 2). Dr. Warren did a wonderful job in corralling this somewhat disparate, yet vitally important, part of our specialty into the Aesthetic volume in the 3rd edition but felt that the task of doing it again, though a labor of love, was more than he wanted to take on. Similarly, Dr. Jim Grotting who did a masterful job in the last edition on the Breast volume, decided that doing a major revision should be undertaken by someone with a fresh perspective and Dr. Maurice Nahabedian stepped into that breach. I hope you will like the changes you see in both of these volumes.

Dr. Allen Van Beek was the video editor for the last edition and he compiled an impressive array of movies to complement the text. This time around, we wanted to go a step further and though we've considerably expanded the list of videos accompanying the text (there are over 170), we also added the idea of lectures accompanying selected chapters. What we've done here is to take selected key chapters and include the images from that chapter, photos and artwork, and create a narrated presentation that is available online; there are annotations in the text to alert the reader that this is available. Dr. Daniel Liu, who has taken over from Dr. Van Beek as multimedia editor (rather than video editor) has done an amazing job in making all of this happen. There are over 70 presentations of various key chapters online, making it as easy as possible for you, the reader, to get as much knowledge as you can, in the easiest way possible from this edition. Many of these presentations have been done by the authors of the chapters; the rest have been compiled by Dr. Liu and myself from the content of the individual chapters. I hope you find them useful.

The reader may wonder how this all works. To plan this edition, the Elsevier team, headed by Belinda Kuhn, and I, convened a face-to-face meeting in San Francisco. The volume editors, as well as the London based editorial team, were present. We went through the 3rd edition, volume by volume, chapter by chapter, over an entire weekend. We decided what needed to stay, what needed to be added, what needed to be revised, and what needed to be changed. We also decided who should write the various chapters, keeping many existing authors, replacing others, and adding some new ones; we did this so as to really reflect the changes occurring within the specialty. We also decided on practical changes that needed to be made. As an example, you will notice that we have omitted the complete index for the 6 Volume set from Volumes 2-6 and highlighted only the table of contents for that particular volume. The complete index is of course available in Volume 1 and fully searchable online. This allowed us to save several hundred pages per volume, reducing production costs and diverting those dollars to the production of the enhanced online content.

In my travels around the world since the 3rd edition was published, I've been struck by what an impact this publication has had on the specialty and, more particularly, on training. Everywhere I go, I'm told how the text is an important part of didactic teaching and a font of knowledge. It is gratifying to see that the 3rd edition has been translated into Portuguese, Spanish, and Chinese. This is enormously encouraging. I hope this 4th edition continues to contribute to the specialty, remains a resource for practicing surgeons, and continues to prepare our trainees for their future careers in Plastic Surgery.

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September, 2017

[1] Chandra R, Agarwal R, Agarwal D. Redefining Plastic Surgery. *Plast Reconstr Surg Glob Open*. 2016;4(5):e706.

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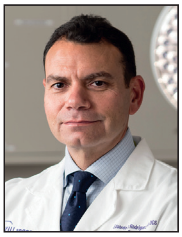

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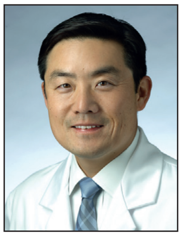

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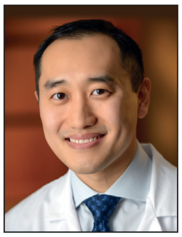

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Peter C. Neligan, MB, FRCS(I), FRCSC, FACS

This completely updated volume represents this generation's brightest minds in hand and microvascular surgery. I am indebted to my colleagues and friends from around the globe for their hard work and eloquent writing, and to our talented staff at Elsevier. It is our hope that this text will continue to serve as a guide for the optimal treatment of all our patients. I am fortunate to have two families to thank: the students, residents, fellows, and faculty at Stanford University who stimulate and enrich me intellectually; and my own loved ones, my wife Dr. Harriet Walker Roeder, and girls Julia, Kathleen, and Cecilia, who sustain me in every way.

James Chang, MD

Dedicated to future plastic surgeons. Take up the torch and lead us forward!

Introduction

Plastic surgery contributions to hand surgery

James Chang

Although references to surgery of the hand date back to Hippocrates in ancient Greece, the dedicated specialty of hand surgery is relatively young. The Second World War is thought to be the major driving event for the development of hand surgery as a separate surgical discipline. This modern specialty was founded by a combination of general surgeons, plastic surgeons, orthopedic surgeons, vascular surgeons, and neurosurgeons. Hand surgery has remained unique in that it is a regional specialty instead of a tissue specialty – its practitioners are ideally trained in managing problems affecting all component tissues of the hand. This introduction chronicles the role plastic surgery has played in the development of hand surgery as a surgical specialty. Furthermore, it predicts how plastic surgery will influence the future direction of hand surgery.

Origins of hand surgery

Henry C. Marble, in Flynn's classic textbook, *Hand Surgery*, found the earliest references to surgery of the hand by Hippocrates (460–377 BC) in ancient Greece.[1] In his writings, Hippocrates described methods to reduce wrist fractures and also highlighted the importance of well-fitting, clean dressings to the hand. A later Greek physician, Heliodorus, described his technique for amputation of a finger with specific reference to dissecting adequate skin flaps with which to cover the remaining bone. While Galen (131–201 AD) confused tendons with nerves and cautioned against suturing tendons for fear of "nervous spasms",[2] Avicenna (981–1038 AD),[3] an Arabian physician, wrote detailed descriptions of tendon repair in medieval times. Other references to hand surgery have been found in history, but comprehensive care of the hand was not truly developed until the 20th century.

An understanding of human anatomy has been critical to both plastic surgery and hand surgery, and therefore, the history of anatomy has paralleled the development of these two surgical disciplines. J. William Littler reviewed the influence of famed anatomists on hand surgery.[4] Perhaps these anatomists were drawn to the hand as the most intricate of body parts – the ultimate challenge to their craft. In the Renaissance period, Leonardo da Vinci (1452–1519) used his artistic genius to create extraordinarily accurate representations of the hand. His knowledge of anatomy was acquired from over 100 human dissections and ultimately resulted in a collection of 779 anatomical drawings.[5]

Andreas Vesalius (1514–1564) (Figs. 0.1 & 0.2) published his monumental work *De Corporis Humani Fabrica* in 1543 with many engravings dedicated to the hand.[5] Like da Vinci, Vesalius relied on his own dissections of cadavers rather than accepting the dogma found in previous medical texts. His observations refuted the inaccuracies found in the earlier writings of Galen and his disciples. Modern-day hand surgeons J. William Littler and Robert A. Chase have both credited Sir Charles Bell (1774–1842) as the foremost anatomist of the hand.[6] His *Fourth Bridgewater Treatise – The Hand: Its Mechanism and Vital Endowments as Evincing Design* (1834) remains a classic essay on the anatomic and functional aspects of the hand.[7]

In addition to anatomy, two more recent achievements allowed hand surgery to develop into a unique specialty in the modern era. On October 16, 1846 at the Massachusetts General Hospital, Dr. William Morton delivered sulfuric ether fumes to a patient undergoing excision of a neck mass by Dr. John Collins Warren.[8] For the first time, adequate anesthesia was performed, thus allowing the possibility of more complex reconstructive procedures in both plastic surgery and hand surgery.

The second major achievement was an understanding of microbiology with resulting advances in sterile technique and antibiotics.[9] In the 1860s, Louis Pasteur's work with fermentation introduced the field of bacteriology. Semmelweis, in Vienna, and Lister, in Britain, developed antiseptic surgery with the early use of carbolic acid as a disinfectant. In the 20th century, several Nobel Prizes marked the importance of the development of antibiotics. Paul Ehrlich a German

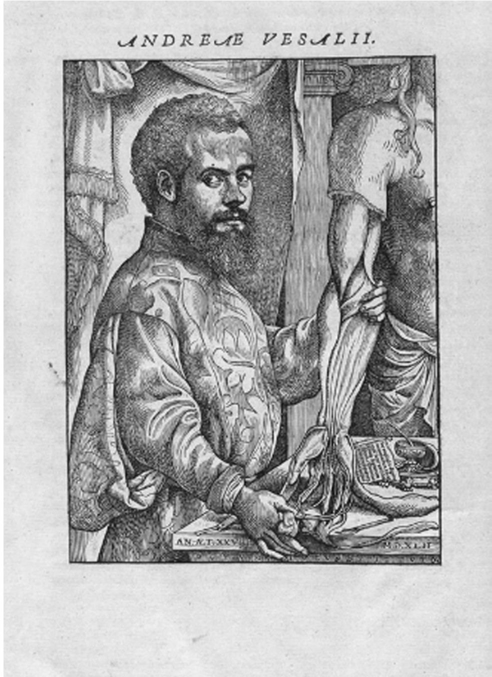

Fig. 0.1 Andreas Vesalius, master anatomist, at the age of 28. *(Reproduced from Vesalius A.* De Humani Corporis Fabrica*. 1543. Reproduced with permission from the British Library.)*

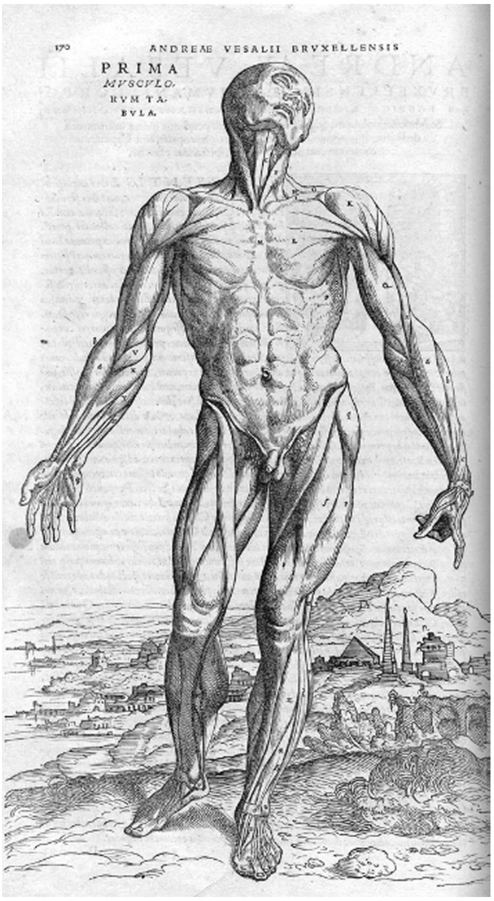

Fig. 0.2 An example of the anatomic illustrations of Stephan van Calcar in the monumental text of Vesalius, *De Humani Corporis Fabrica* (1543). *(Reproduced from Vesalius A.* De Humani Corporis Fabrica*. 1543. Reproduced with permission from the British Library.)*

bacteriologist, developed the principle of "antimicrobial chemotherapy" and received the Nobel Prize in 1908. Another German, Gerhard Domagk, received the Nobel Prize in 1939 for discovering the antibacterial effects of sulfa drugs. Finally, Alexander Fleming shared the Nobel Prize in 1945 for discovering the ability of a mold, *Penicillium notatum* to halt the growth of staphylococcus bacteria. With penicillin and later antibiotics, plastic surgeons and hand surgeons had an armamentarium of agents to control infections.

Over the course of this history, how has plastic surgery contributed to the development and progress of hand surgery? Like hand surgery, plastic surgery became a separate surgical specialty in the US only in the 20th century with the founding of the American Association of Oral and Plastic Surgeons (later shortened to the American Association of Plastic Surgeons) in 1921. The American Board of Plastic Surgery was not established until 1938. However, plastic surgery has profoundly influenced hand surgery, and this influence has predated formal associations and boards. In other words, surgeons throughout history have used plastic surgery principles before they were known as "plastic surgeons". Therefore, early plastic surgery contributions to hand surgery are best chronicled by reviewing the development of plastic surgery principles and how they have been applied to hand surgery.

Principles of plastic surgery and their application to hand surgery

Sushruta, a Hindu surgeon in India around the first century AD, performed reconstruction of the nose using pedicled flaps from the face – either forehead or cheek. He described the operation as follows:

> *The physician should take the leaf of a tree the same size as the nose and apply it to the cheek in such a way that a stem is still adherent. Then he stitches the cheek with needle and thread, scarifies the stump of the nose and quickly but carefully places the flap in the nose. After the transplanted piece has grown, the stem is cut off. In like manner the flap might be turned up from the upper or lower arm and attached to the nose – with the arm over the head.*[1]

This description included the basic plastic surgery principles of precise patterning of the defect, preparation of the recipient bed, and the use of local and distant flaps, all which have had obvious applicability to soft-tissue reconstruction of the hand.

Another famed surgeon, Ambrose Paré (1510–1590), offered principles that allowed for optimal care of battlefield wounds, including the upper extremity: "to enlarge the wound for drainage; to remove bone splinters and foreign bodies from wounds; to control hemorrhage with ligatures; not to encourage suppuration; and to amputate through sound tissues."[1] Paré's use of ligatures during amputation controlled hemorrhage and saved countless lives on the battlefield (Figs. 0.3 & 0.4). His principles of wound care would later be applied directly to the enormous number of battlefield casualties of World War II. In addition, Paré popularized the anatomic drawings of Vesalius amongst surgeons, and even designed elaborate prostheses for upper extremity amputees, victims of the French wars of the 1500s. Paré was perhaps the quintessential upper extremity trauma surgeon.

Fig. 0.3 Ambrose Paré applying a ligature during battlefield amputation. Wood engraving by C. Maurand. *(Reproduced with permission from The Wellcome Trust L0018530.)*

Gaspare Tagliacozzi (1545–1599) did not invent the Italian method of nasal reconstruction, which has been generally attributed to Branca. However, Tagliacozzi, a professor of medicine and anatomy in Bologna, did popularize this technique of attaching a medial upper arm skin flap to the nasal defect. In addition, specialized leather band contraptions were devised to immobilize the patient during the period of flap revascularization (Fig. 0.5). His detailed textbook, *De Chirurgia Curtorum per Insitionem,* was published in 1597 and allowed later generations of surgeons to learn techniques for the transfer of distant pedicled flaps.[5]

As plastic surgeons became more adept at tissue transfer, these innovations were applied to reconstruction of the hand. Carl Nicoladoni (1849–1903) pioneered work on reconstruction of the thumb. Nicoladoni reported on a case of total skin avulsion of the thumb that he treated by a skin flap from the patient's left pectoral region – similar to the thoracoepigastric or random pattern chest flaps still used today.[6] In 1903, his paper, "Further experience with thumb reconstruction", described the pedicled toe transfer to the thumb that continues to bear his name. Microsurgeons today have obviated the need for the uncomfortable positioning of this transfer; nevertheless, Nicoladoni deserves credit for the ingenuity behind the toe-to-hand transfer. Plastic surgeon George H. Monks (1853–1933) transferred a composite skin island flap from the forehead on the superficial temporal arteriovenous pedicle to a lower-eyelid defect.[6] The use of island flaps would later be applied to the hand with the neurovascular island flaps of Littler, and, more recently, with the dorsal metacarpal artery flaps. Even Sir Harold Gillies (1882–1960) who, with Millard, codified the principles of plastic surgery and was one of history's most influential plastic surgeons, turned from the head and neck to the hand and devised a method to lengthen the stump of a thumb, the Gillies "cocked-hat" flap.[10]

Vilray P. Blair (1871–1955) was one of the founding fathers of American plastic surgery.[11] In addition to a large body of work in cleft lip repair and maxillofacial surgery, Blair made two significant contributions to plastic surgery that translated directly to hand surgery. Blair helped redefine the delay phenomenon of Tagliacozzi in a 1921 article, "The delayed transfer of long pedicled flaps in plastic surgery". Blair and his disciple, James Barrett Brown (1899–1971), described a new technique of harvesting skin for skin grafting in a paper published in *Surgery, Gynecology, and Obstetrics* entitled "The use and uses of large split skin grafts of intermediate thickness".[12] This simple and reproducible method of harvesting split-thickness skin improved on the previous techniques of Thiersch and would have a tremendous impact on the reconstruction of hand burns and other wounds in World War II.

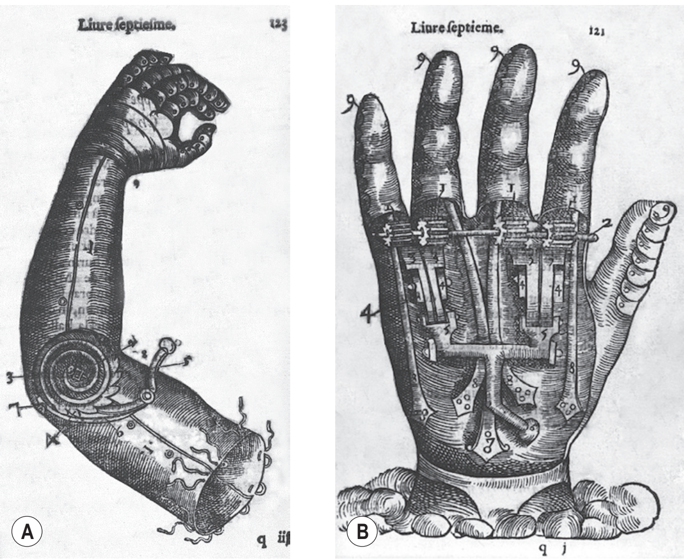

Fig. 0.4 Examples of Paré's designs for prostheses. *(Reproduced from* Les Oeuvres de M. Ambroise Paré, *1575, p. 916–917.)*

Fig. 0.5 Tagliacozzi's immobilization device after arm-to-nose pedicled transfer. *(Reproduced from Typ 525.97.820 with permission from Houghton Library, Harvard University.)*

Origins of modern hand surgery

With this historical background in wound management, flap transfer, and skin grafting, plastic surgeons were poised to contribute to the founding of modern hand surgery. World War II was the crucible in which hand surgery became a separate specialty. Prior to the outbreak of this war, two surgeons were instrumental in hand surgery's early development. In 1939, Allen B. Kanavel published his *Infections of the Hand*,[13] and for the first time, a comprehensive approach to the myriad of hand infections and treatments was described. Even at that early time, Kanavel stressed the importance of hospitalization for hand infections, intravenous hydration, and placing the hand at rest.

Sterling Bunnell (1882–1957) has been widely regarded as the father of hand surgery. The first edition of Bunnell's comprehensive textbook, *Surgery of the Hand*,[14] was published in 1944, and remained the classic reference for many years. He was a general surgeon but believed in the importance of plastic surgery principles, and as the consummate hand surgeon, was able to apply plastic, orthopedic, and vascular principles equally to hand surgery. Marble recounted Bunnell's mastery:

> He insisted on all of the teachings of the past masters, stressing particularly the gentle handling of the tissues. He called this atraumatic surgery. He exercised his skill also in plastic, bone, tendon, nerve, blood vessel, and muscle surgery to reconstruct crippled hands. He showed that tendons could be grafted to substitute for lost ones, and could be transferred to give function to useless digits or joints. He taught that nerves could be grafted and that whole fingers could be moved about for better function. Thus he opened the door for the complete reconstruction of the injured hand.[1]

The specialty of hand surgery in the US really developed in the field hospitals and regional medical referral centers established during the Second World War. During those years, massive numbers of surviving casualties with upper extremity injuries, an organized resuscitation and transportation service, and increasing sophistication within the fields of general surgery, plastic surgery, orthopedic surgery, vascular surgery, and neurosurgery together formed the critical mass necessary for accelerated technical and educational development.

The high volume of hand injuries requiring care in World War II was unprecedented. Unlike the trench warfare of World War I when head and neck wounds were common, World War II involved open warfare with rapid movements and grenades, leading to a greater likelihood of upper extremity injuries. In the early years of the war, soldiers with injured hands and upper extremities were placed into individual hospitals and distributed somewhat arbitrarily on to orthopedic, general surgery, plastic surgery, and neurosurgery wards depending on the nature of the injury and the availability of beds. It became evident that specialized interdisciplinary care of the hand patient was necessary. In a masterpiece of organizational effort, regional hand referral centers were established in US military hospitals. Colonel J.J. Reddy and Colonel F.V. Kilgore together established the first ward designated for hand surgery at Cushing General Hospital in Framingham, Massachusetts.[15] Plastic surgeon Captain (later Major) J. William Littler was assigned to this ward and supervised the first service specifically dedicated to care of the injured hand. Joint conferences involving plastic surgery, orthopedic surgery, and neurosurgery were established and, within a short time, four complete wards dedicated to hand surgery were in operation.

Dr. Littler's unit was used as a model by Surgeon General Norman T. Kirk to establish nine military referral centers throughout the US.[15] Sterling Bunnell served as civilian surgical consultant to the Secretary of War and visited each referral center to teach hand surgery.

Simultaneously, advances in plastic surgery had provided effective and reliable methods of wound coverage ranging from split- and full-thickness skin grafts to local and distant pedicled flaps. This ability to cover wounds was critical to the development of hand surgery. Because wound coverage was a priority, the regional hand centers established across the US were situated in hospitals that had been already designated as plastic surgery centers.

Plastic surgeons were instrumental in this early phase of development in American hand surgery because of their expertise in wound care and trauma reconstruction. In March 1945, Lieutenant Colonel Eugene M. Bricker outlined in an Army memorandum the principles of plastic surgery relevant to hand surgery:

1. Conservative, careful and thorough debridement of the primary wound is essential. Primary closure is not advised in an evacuation hospital, but skin flaps can be dressed back into place.
2. Splint purposefully, maintaining the palmar arch and flexion of the metacarpophalangeal joints.
3. Bring about delayed closure as early as possible, preferably on the third or fourth day, by simple closure, split graft or pedicle graft, according to the necessities of the case.
4. Use traction only when it is urgently indicated, and then for a minimum length of time.
5. Concentrate on maintenance of such function as remains following certain severe types of injury. Restoration of the injured part should not be attempted, and healing should be accomplished as rapidly as possible. Amputation of an irreparably damaged finger is justified.
6. Institute active motion as early as possible, and supplement by occupational therapy when healing has occurred.
7. Try to prevent edema and infection in open wounds. Proper debridement, proper dressings, proper splinting, and effective elevation of the hand will prevent this development.
8. Manage an open wound aseptically as long as it remains open. Aseptic management implies the use of masks and of instruments or gloves, whether or not the wound is infected.[16] These principles served as the foundation for acute treatment of traumatic hand injuries.

Developments after World War II

Immediately after World War II, plastic surgeons continued to have a profound influence on hand surgery. In 1946, plastic surgeon Darrel T. Shaw and general surgeon Robert Lee Payne published a landmark paper entitled, "One stage tubed abdominal flaps".[17] This paper described an axial flap based on the superficial inferior epigastric vessels for composite tissue transfer to the hand. The development of reliable composite tissue transfer allowed early coverage of extensive hand and upper extremity defects. Sir Archibald McIndoe, a disciple of Gillies, established several burn facilities in England and refined techniques in burn excision and reconstruction of the hand.[18]

The patients wounded during the battles of World War II returned to the US for further reconstructive surgery by an increasingly better-trained cadre of hand surgeons. In order to coordinate this explosive growth in hand surgery, representatives from general surgery, plastic surgery, and orthopedic surgery combined to form the American Society for Surgery of the Hand in 1946.[19] The first annual meeting was held on January 20, 1946 at the Blackstone Hotel in Chicago, Illinois, with Sterling Bunnell as the first president. Plastic surgeons figured prominently – of the 35 founding members, 13 (37%) came from plastic surgery backgrounds.[20]

Hand surgery underwent another period of accelerated productivity during the Korean War. By that time, the US military had experience in organizing regional referral centers for reconstruction of the hand. Dr. J William Littler took on Bunnell's former role and was appointed as Hand Surgery Civilian Consultant to the Military.[6] Littler's unrivaled experience from World War II and then the Korean conflict allowed him to become perhaps the most famous of plastic hand surgeons. His achievements have included the Littler digital neurovascular transfer and countless other surgical innovations bearing his name, in addition to his legendary anatomic sketches of the hand and long list of trainees who have become distinguished hand surgeons themselves. Other plastic surgeons who were involved in the Korean War effort included Robert A. Chase and Earle Peacock. Robert A. Chase returned from his military duty to embark on a lifelong effort of developing educational aids related to functional anatomy of the hand. Earle Peacock contributed original laboratory work on wound healing, particularly related to flexor tendon wound healing.

The era of microsurgery

Hand surgery underwent an intense period of laboratory and clinical activity in the 1960s and 1970s devoted to microsurgery and free tissue transfer. In 1963, Goldwyn *et al.* presented their work on abdominal free flaps in dogs, based on the inferior epigastric vessels.[21] This investigative work was further developed by Krizek *et al.* in 1965.[22] Together, these plastic surgeons, along with O'Brien,[23] Taylor *et al.*[24] and many others throughout the world, established the possibility of free tissue transfer that liberated the hand surgeon from the anatomic limitations of local tissue transfer.

Replantation of fingers and other body parts came into reality via an international effort of plastic surgeons, orthopedic surgeons, and general surgeons. The first successful replantation of an upper arm amputation by Malt and McKhann was carried out in 1962, and the first successful replantation of an amputated thumb was performed in 1968 by Komatsu and Tamai. Since then, replantation teams have been organized in major hospitals, and microsurgical techniques have become an integral part of the training of hand surgeons. The techniques of replantation in the upper extremity have been extrapolated to successful replantation of other parts of the body, including the lower limb, the scalp, the ear, portions of the lip and nose, and the penis, and have led directly to the further evolution of elective microsurgical free tissue transfer. In addition, plastic surgeons have devised innovations to improve the success rates of replantation, including the use of Y-shaped interposition vein grafts in multiple-digit replantations[25] and replantation of fingers distal to the proximal interphalangeal joint.[26]

Plastic surgeon Harry J. Buncke helped pioneer the toe-to-thumb transplant in animal models, and eventually in humans. His efforts in the past 40 years have made him one of the fathers of American microsurgery.[27] Beyond the earlier work of Littler on thumb reconstruction, plastic surgeons have continued to contribute greatly to the refinement of various operations, including the toe-to-hand transfer[28,29] and the great-toe wraparound free flap of Morrison *et al.*[30]

Critical to reconstruction of the hand with both pedicled flaps and free flaps has been a detailed knowledge of anatomy as it relates to vascular distributions to muscle and skin. McCraw *et al.* popularized the use of musculocutaneous flaps[31] and Mathes and Nahai developed an atlas of these muscle and musculocutaneous flaps, which has been an invaluable reference for the reconstructive surgeon.[32] Ian Taylor and his plastic surgery colleagues have described the vascular territories of skin flaps. Taylor's angiosome theory, where the body is divided into different vascular territories to the skin, originating from deeper source arteries, has allowed surgeons to design flaps with reliable perfusion. In addition, second-generation flaps, based on smaller vessels, may be possible with an understanding of this intricate anatomy.

Plastic surgeons have also continued to be involved in the political and educational development of hand surgery. In 1970, a second hand organization – the American Association for Hand Surgery (AAHS) – was founded.[33] By the fall of 1971, there were 65 full members. As in the American Society for Surgery of the Hand, plastic surgeons played an instrumental role. The first meeting in 1971 immediately preceded the annual American Society of Plastic and Reconstructive Surgeons meeting. This arrangement symbolized the influence and participation of plastic surgeons in the AAHS that continues today.

Recent developments

In recent years, significant contributions to hand surgery have been made by plastic surgeons. One area of intense study in the past several decades has been peripheral nerve repair and reconstruction. Millesi *et al.*[34] published a landmark paper in 1972 on interfascicular nerve grafting of median and ulnar nerves. Since then, nerve grafting, as well as autogenous vein grafting of nerve defects, has helped improve results of nerve reconstruction.[35,36] Mackinnon and Hudson[37] have examined the possibility of immunosuppression for allograft nerve transplantation to bridge extensive defects where autogenous donor nerve may not be sufficient, and more recently pioneered the field of nerve transfers.[38] Several plastic surgeons, including Terzis *et al.*[39] and Hentz and Narakas,[40] have published reports of their considerable experience on reconstruction of brachial palsy injury. Their dedication to the comprehensive reconstruction and rehabilitation of these devastating injuries has resulted in improved surgical outcomes.

Beyond replantation, more intricate microvascular operations have been undertaken by plastic hand surgeons to restore form and function to the hand. Although the indications are limited, microvascular transfer of a toe metatarsophalangeal joint to recreate a metacarpophalangeal joint has been shown to be possible.[41] Further advances in microsurgical reconstruction of the hand include functional free muscle transfer. Manktelow and McKee's landmark paper in 1978 introduced the concept of a free gracilis or free pectoralis major muscle transfer with motor nerve coaptation to restore active finger flexion.[42]

Plastic surgeons have also been at the forefront of congenital hand surgery.[43] Graham Lister published one of the first significant series of toe-to-hand microvascular transfers in children, ushering in a new era of complex reconstruction for congenital hand problems.[44] Other authors, including Gilbert[45] and Buck-Gramcko,[46] have also published their series. More recently, Neil Jones has added his work on pediatric toe-to-hand transfers to previous contributors, thus refining these technically challenging procedures.[47] In addition, Joseph Upton *et al.*[48] reported on their unrivalled experience with excision and reconstruction of vascular anomalies in the upper extremity.

The plastic surgery techniques of flap dissection have been used to develop newer flaps intrinsic to the hand and upper extremity such as vascularized bone flaps from the distal radius. There is much excitement in using these pedicled bone flaps for revascularization of the scaphoid in scaphoid nonunion and avascular necrosis, or revascularization of the lunate in Kienbock's disease.[49] These second-generation flaps may lead to other intrinsic flaps that will also be useful for bone and ligament reconstruction.

Plastic surgeons know of their legacy of involvement in the field of organ transplantation. Much of the pioneering work on allograft rejection and homograft tolerance by Sir Peter Medawar and others was derived from experimentation with skin grafts in various animal models.[9] Joe Murray, the only plastic surgeon ever to receive the Nobel Prize, received it for his work on transplantation, including the first human kidney transplantation in 1954.[9] With newer immunosuppressive agents and greater acceptance of the risks of transplantation, human hand allograft transplantation has now become a reality.[50] While the ultimate success of these early operations remains to be seen, reaching these new frontiers in hand reconstruction as well as in other forms of composite tissue allotransplantation is now possible.

Future directions

An accomplished hand and plastic surgeon once wrote:

> *I learned about hand surgery's battle against scar adherence and contraction and that the Z-plasty can be a major and intriguing weapon in that battle in other parts of the body as well as in the hand. I thought a lot about the Z-plasties that year and used them often, in multiple parts of the body, always trying to pick the optimum size and the best orientation, trying to decide which of the two parallel sides of the Z-plasty's diamond would be most advantageous for mimicking the wrinkle lines, and trying to avoid running into features not to be moved or, occasionally, to something on or in one of the flaps … Ever since, I have looked upon the Z-plasty as a little bit of magic.*[51]

That surgeon was Leonard T Furlow Jr, who took the Z-plasty from the scarred hand to the cleft palate. It is an excellent example of the intellectual interplay between plastic surgery and hand surgery.

Current plastic surgery research has focused on growth factor technology to inhibit scarring or to augment bone growth, wound healing,[52] and angiogenesis. Tissue engineering may allow formation of ample supplies of bone, cartilage,[53] even muscle, skin, and nerve. Virtual reality surgery will help plastic surgeons model and practice complex reconstructive procedures prior to undertaking them. In the next decade, hand surgeons will acquire an armamentarium that includes bone substitutes, tissue-engineered bone, cartilage and nerve, and three-dimensional computer models for complex intracarpal abnormalities. Throughout the chapters of this hand volume, you will find new, pioneering translational work that shapes the future of hand and upper extremity surgery. As in microsurgery, plastic surgeons will lead the way for this new technical revolution in hand surgery.

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Anatomy and biomechanics of the hand

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SYNOPSIS

- The hand is an incredibly designed structure with complex anatomy and precise biomechanics. The hand must be able to produce adequate force to allow performance of activities of daily living. Furthermore, it must ensure coordination of the fingers for precise prehension and fine motor tasks.
- In order to achieve an optimal functional and aesthetic outcome in patients requiring hand surgery, it is thus essential to fully understand the detailed bone, muscle–tendon, aponeurotic, vascular, nerve and lymphatic components.
- Additional challenges arise from the range of possible movements of various articular surfaces, assisted by muscle action and ligamentous support.
- In this chapter, we present the various elements that compose the hand as well as explanations of the biomechanical principles. These are updated according to the latest literature. Additionally, clinical examples will be used to illustrate anatomic principles.

Introduction

During the Renaissance, Vesalius corrected early misconceptions and brought gross anatomy into proper focus. Since that time, many investigators have embellished the basic structural studies with functional, physiologic, and philosophical observations. The forearm and hand have been prominently included in those observations. Sir Charles Bell (1834),[1] in his thought-provoking volume, *The Hand – Its Mechanism and Vital Endowments as Evincing Design*, presented a concept of hand anatomy that places it in proper context with the position of humans in the animal kingdom. Duchenne (1867) carried out detailed analysis of muscular function by isolated electrical stimulation, described in his classic volume, *Physiologie des Mouvements*.[2] Frederick Wood-Jones (1920) probed more extensively into comparative anatomy and anthropology in his excellent work, *The Principles of Anatomy as Seen in the Hand*.[3] Allen B. Kanavel (1925) published his monograph, *Infections of the Hand*, which reported detailed analysis of the spaces and synovial sheaths.[4] *Surgery of the Hand* by Sterling Bunnell (1944) became an indispensable reference during World War II.[5] Emanuel B. Kaplan (1953) produced the nicely illustrated, detailed volume, *Functional and Surgical Anatomy of the Hand*.[6] Detailed studies of the integration of the intrinsic and extrinsic muscles operating the polyarticular digits may be found in the work of Landsmeer,[7–10] Kaplan,[11] Eyler and Markee,[12] Stack,[13] Tubiana and Valentin,[14] and others. More recently, newer flaps intrinsic to the hand and upper extremity have been developed from more detailed investigation into vascular anatomy.[15,16] Lastly, Berger,[17] Viegas *et al.*,[18] and others have expanded our knowledge of the ligamentous anatomy of the wrist.

As a functional puppet, the hand responds to human desires; its motor performance is initiated by the contralateral cerebral cortex. The conscious demands relayed to the hand and forearm from the central nervous controlling mechanism are sent as movement commands. At subconscious levels, such a movement command is broken down, regrouped, coordinated, and sent on as a signal for fixation, graded contraction, or relaxation of a specific muscular unit. The degree of contraction or relaxation is then modified by relayed evidence that the motion created is that desired by the person. The modifying factors arrive centrally from a multiplicity of sensory sources such as the eye, peripheral sensory end organs, and muscle or joint sensory endings.

The surgeon planning reconstructive surgery on the upper extremity must be aware not only of the complex anatomy of the hand and arm, but also of the physiologic interplay of balanced muscular functions under the influence of complex central nervous coordination. The maintenance of physiologic viability by the central and peripheral circulatory and lymphatic systems must also concern the reconstructive surgeon.

This chapter addresses the fundamentals of hand and upper extremity anatomy and highlights clinical pearls, new anatomic descriptions that may aid surgery of the hand, and the fundamentals of biomechanics relevant to the hand surgeon. New pictures and dissection videos are now available for the reader to review important anatomic concepts.

Skin, subcutaneous tissue, and fascia

There is great disparity in the character of the skin and soft-tissue envelope covering the dorsum of the hand and that covering the palm. Dorsal skin is thin and pliable, anchored to the deep investing fascia by loose, areolar tissue. These characteristics, coupled with the fact that the major venous and lymphatic drainage in the hand courses dorsally, serve to explain why hand edema is first evident dorsally. The prominent, visible veins in the subcutaneous tissue make it the standard site in which to evaluate venous filling and limb venous pressure on physical examination. The same characteristics make the dorsum of the hand vulnerable to skin avulsion injuries.

Palmar skin, in contrast, is characterized by a thick dermal layer and a heavily cornified epithelial surface. The skin is not as pliable as dorsal skin, and it is held tightly to the thick fibrous palmar fascia by diffusely distributed vertical fibers between the fascia and dermis. Stability of palmar skin is critical to hand function. At the same time, if scar fixation or loss of elasticity occurs in palmar skin, contractures and functional loss result. The skin of the palm is laden with a high concentration of specialized sensory end organs and sweat glands. The surgeon must understand the relationship of the palmar skin creases and the underlying joints in order to plan precise placement of skin incisions for exposure of joints and their related structures (Box 1.1 & Fig. 1.1).

Examination of hand skin during normal ranges of motion in various planes is important in planning incisions or geometrically rearranging lacerations that might result in disabling scar contractures. Most loss of elasticity and some longitudinal shortening are compensated for adequately by mobility and elasticity of the uninjured dorsal skin. On the palmar aspect, however, scar shortening and inelasticity of the skin may result in contracture. The nature of palmar skin, its stabilizing fixation to the palmar fascia, and its position on the concave side of the hand are the bases for such contractures. Littler outlined the specific sites in the palm where a longitudinal scar would impede extension.[20] For example, in each digit the geometry has been worked out by noting each joint axis and the kissing surfaces of the palmar skin in full flexion. These diamond-shaped skin surfaces should not be shortened and rendered inelastic by longitudinal scars if limitation of extension is to be avoided (Fig. 1.2).

BOX 1.1 Clinical pearl: Kaplan's cardinal line

Hand anatomist Emanuel Kaplan described specific surface lines that would aid surgeons in locating key structures in the palm of the hand. The cardinal line has often been misquoted; therefore we refer to Kaplan's classic hand text, *Functional and Surgical Anatomy of the Hand*.[19] Kaplan's cardinal line is drawn from the apex of the first web space to the distal edge of the pisiform bone (see Fig. 1.1). Two longitudinal lines are drawn from the ulnar aspect of the middle finger and the ulnar aspect of the ring finger. These will cross the cardinal line. The intersection of the cardinal line and the longitudinal line from the ulnar side of the middle finger corresponds to the motor branch of the median nerve. The intersection of the cardinal line and the longitudinal line from the ulnar side of the ring finger corresponds to the hook of the hamate. The motor branch of the ulnar nerve is found on the cardinal line, equidistant between the hamate and pisiform. See Kaplan's original text for additional surface markings.

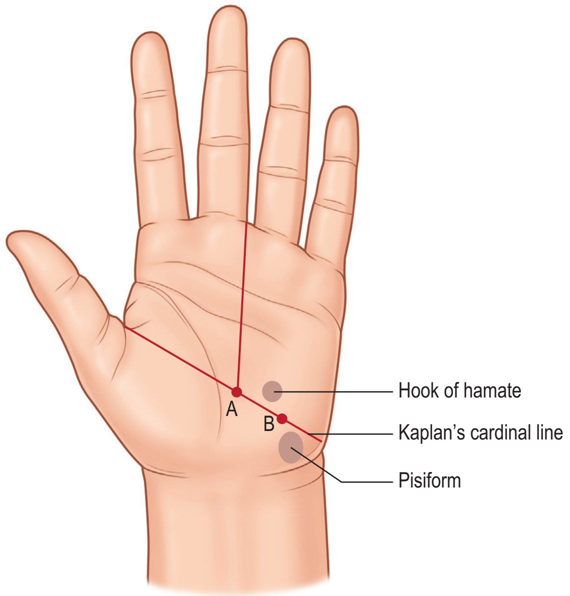
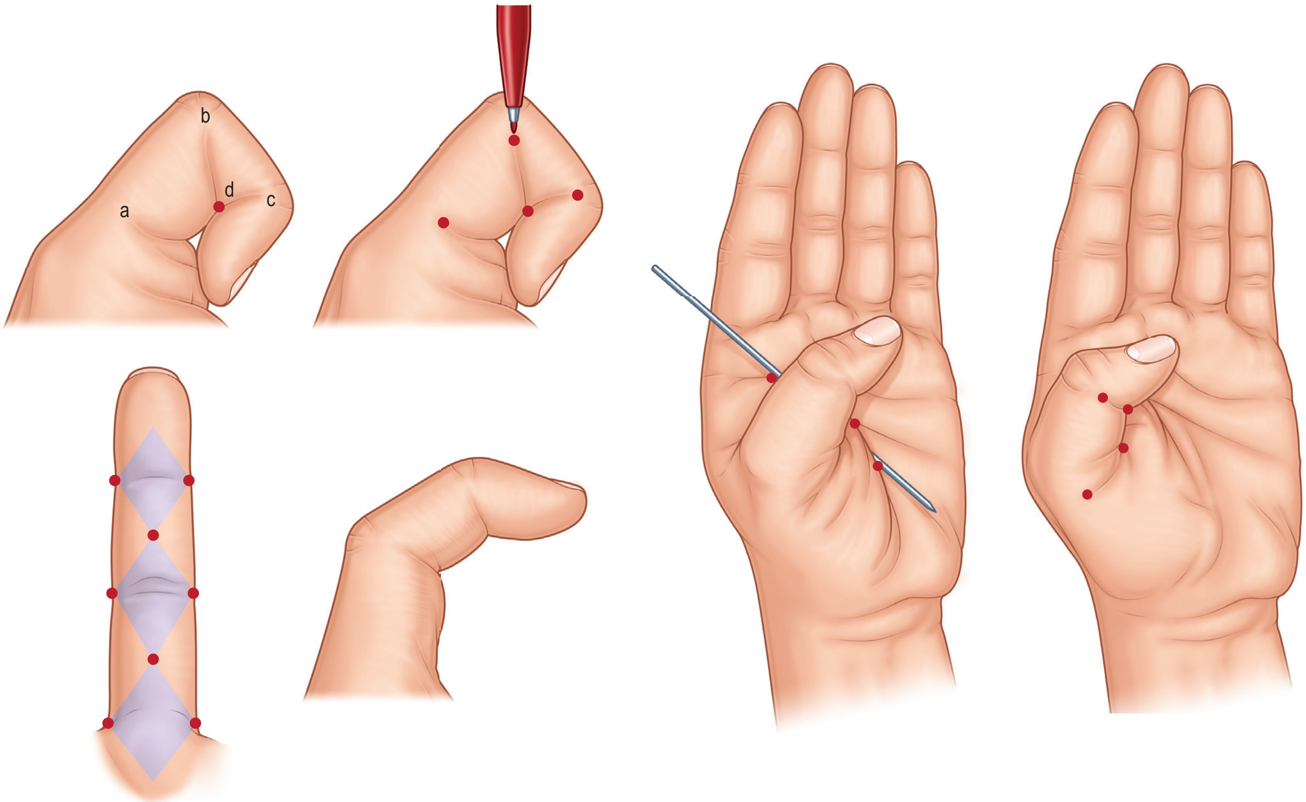


Fig. 1.1 Kaplan's cardinal line, along with lines from the ulnar aspect of the middle finger and the ulnar aspect of the ring finger. Point A corresponds with the motor branch of the median nerve and point B with the motor branch of the ulnar nerve.

The palmar fascia consists of resistant fibrous tissue arranged in longitudinal, transverse, oblique, and vertical fibers (Fig. 1.3). The longitudinal fibers concentrate at the proximal origin of the palmar fascia at the wrist, taking origin from the palmaris longus when it is present (in about 80–85% of individuals). The fascia at this level is separable from the underlying flexor retinaculum/carpal ligament, being identified by the longitudinal orientation of its fibers in contrast to the transverse fibers of the retinaculum. The palmar fascia fibers fan out from this origin, concentrating in flat bundles to each of the digits. Generally, the fibers spread at the base of each digit and send minor fibers to the skin and the bulk of fibers distal into the fingers, where they attach to tissues making up the fibrous flexor sheath of the digits. There are attachments of the fascia to the volar plate and intermetacarpal ligaments at each side of the flexor tendon sheath at the level of the metacarpal heads.

Transverse fibers are concentrated in the midpalm and the web spaces. The midpalmar transverse fibers, although intimately associated with the longitudinal bundles, lie deep to them and are inseparable from the vertical fibers that concentrate into septa between the longitudinally oriented structures passing to the fingers. This system of palmar transverse fibers makes up what Skoog (1967) called the transverse palmar ligament.[21] In fact, the transverse fibers form the roof of tunnels at this point that act as pulleys for the flexor tendons proximal to the level of the digital pulleys. Biomechanical evaluation of the palmar aponeurosis pulley has demonstrated that isolated sectioning did not change the work of flexor tendons or load efficiency.[22] Nevertheless, this pulley has been implicated as contributing to the etiology of trigger finger.[23]



A

B

Fig. 1.2 (A,B) Schematic representation of the joint axes. The longitudinal dimensions in the midpalmar and mid-dorsal aspect of the digits change maximally. The midaxial line through the three joint axes does not change in length with flexion and extension. Palmar incisions placed longitudinally produce contracture if they pass across the palmar diamonds delineated by lines joining the joint axes (after Littler). Transverse incisions avoid the occurrence of flexion scar contractures. The same principle applies at the wrist. *(Redrawn after Chase RA.* Atlas of Hand Surgery*, vol 1. Philadelphia: WB Saunders, 1973.)*

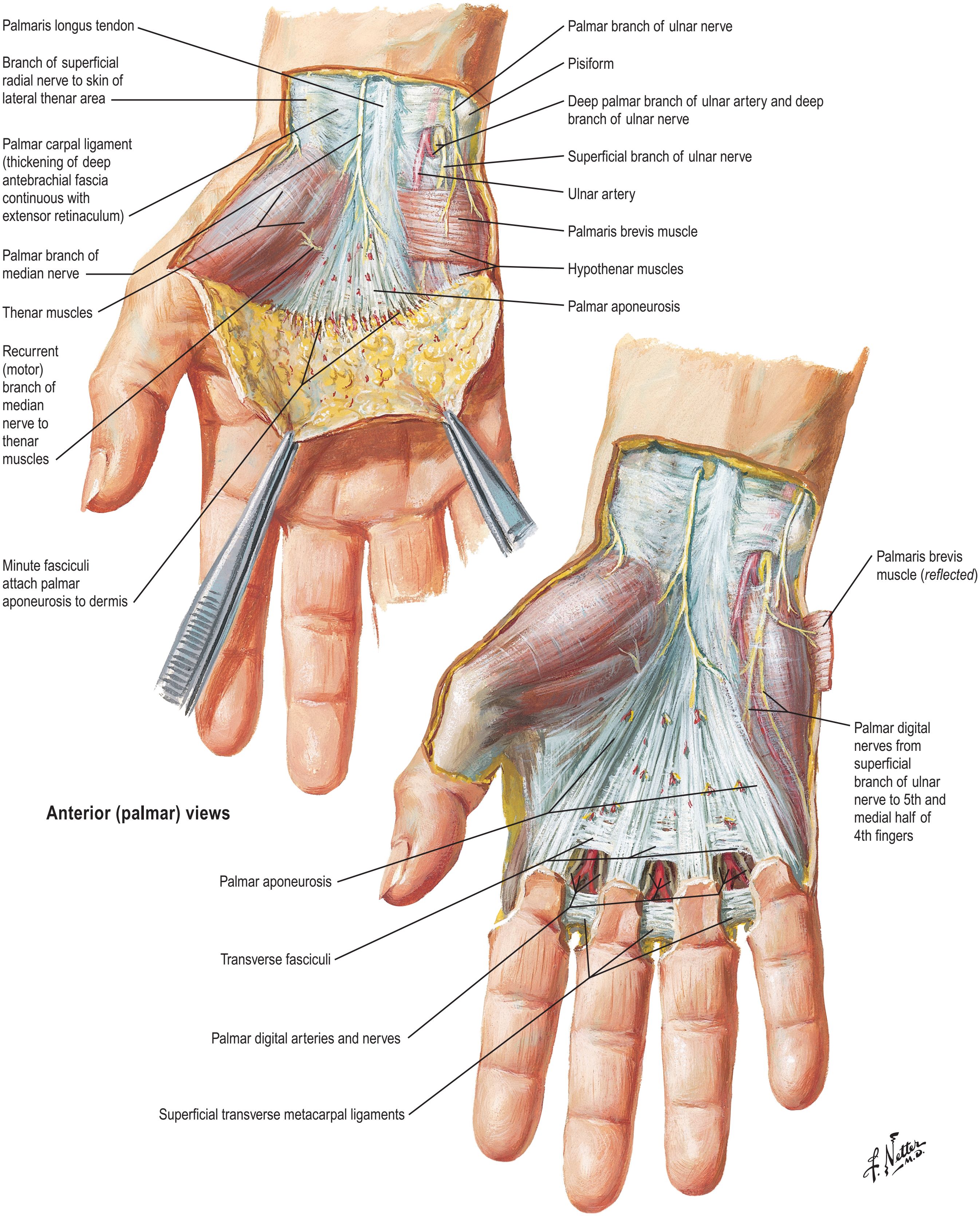


Fig. 1.3 Superficial dissection of the palm, showing orientation of the palmar fascia. *(Reprinted with permission from www.netterimages.com © Elsevier Inc. All Rights Reserved.)*

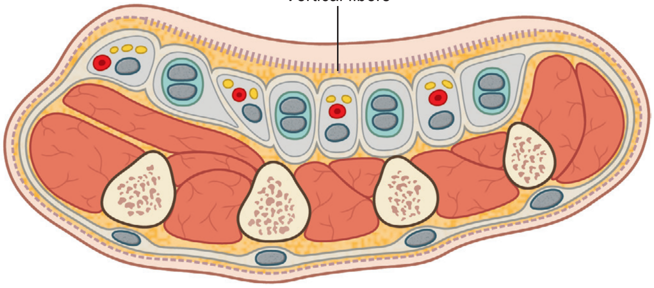


Fig. 1.4 The palmar fascia with its longitudinal, transverse, and vertical fibers. The longitudinal fibers take origin in the palmaris longus (when present). Transverse fibers are concentrated in the distal palm supporting the web skin and in the midpalm as the transverse palmar ligament. Vertical fibers extend superficially as multiple, tiny tethering strands to stabilize the thick palmar skin. The deep vertical components concentrate in septa between the longitudinally oriented structures in the fingers. *(Redrawn after McCarthy JG.* Plastic Surgery*. Philadelphia: WB Saunders, 1990.)*

Longitudinal fibers pass toward the palmar surface of the thumb, but these fibers are generally less numerous and sometimes difficult to identify. The thumb fibers blend into the deep fascia overlying the thenar muscles. The ulnar extreme palmar fascia blends with the hypothenar fascia. The proximal one-third of this border is the attachment site of the palmaris brevis muscle. Laterally, the muscle attaches to the hypothenar skin and hypothenar fascia.

The vertical fibers of the palmar fascia, which lie superficially to the tough triangular membrane made up by the longitudinal and transverse fibers, consist of abundant vertical fibers to the palm dermis (Fig. 1.4). Deep to the palmar fascia, the vertical fibers coalesce into septa, or the "perforating fibers of Legueu and Juvara",[24] forming compartments for flexor tendons to each digit and separate compartments for the neurovascular bundles together with the lumbrical muscles. There are eight such compartments, which extend proximally to about the midpalm. Proximal to this, there is a common central compartment.[25] The marginal septa extend more proximally than the seven intermediate septa closing the central compartment laterally and medially. The major septum between the index flexor tendons and the neurovascular and lumbrical space to the third interspace attaches to the third metacarpal, dividing the thenar or adductor space from the midpalmar space. Knowledge of these vertical compartments aids dissection and identification of structures in operations such as trigger-finger release and Dupuytren's fasciectomy (Fig. 1.5).

In the fingers, two important bands of fascia are named Grayson's ligaments and Cleland's ligaments. Grayson's ligaments are volar to the neurovascular bundles and are quite flimsy. The much stouter Cleland's ligaments are dorsal to the neurovascular bundles. These two fascial sheets help contain and protect the ulnar and radial digital arteries and nerves (Fig. 1.6).

Bones and joints

Hand elements

The ability of the hand to resist and create powerful gross action, combined with its capacity to perform intricate fine movements in multiple planes, reflects the masterful construction of its supporting architecture. Reducing the hand to its supporting skeleton and its restraining ligaments reveals the architectural basis for its varied function. A study of the range of joint motions in the hand and forearm with all motor elements removed discloses the full range and limitations that the skeleton imposes on hand function.

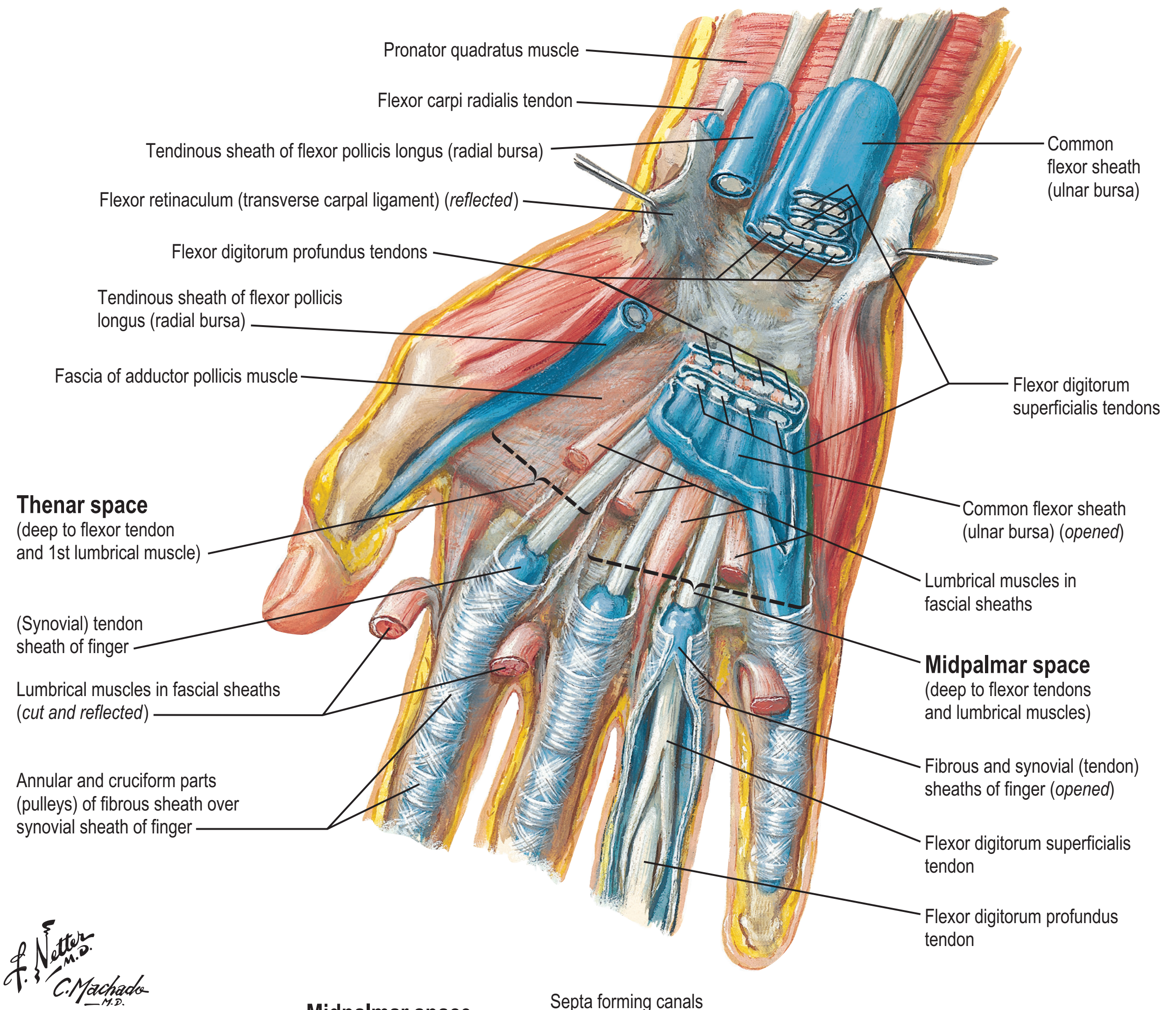
The hand skeleton is divisible into four elements:

1. The fixed unit of the hand, consisting of the second and third metacarpals and the distal carpal row.
2. The thumb and its metacarpal with a wide range of motion at the carpometacarpal joint. Five intrinsic muscles and four extrinsic muscles are specifically influential on thumb positioning and activity.
3. The index digit with independence of action within the range of motion allowed by its joints and ligaments. Three intrinsic and four extrinsic muscles allow such digital independence.
4. The third, fourth, and fifth digits with the fourth and fifth metacarpals. This unit functions as a stabilizing vise to grasp objects for manipulation by the thumb and index finger, or in concert with the other hand units in powerful grasp (Fig. 1.7).

The distal row of carpal bones forms a solid architectural arch with the capitate bone as a keystone. The articulations of the distal carpals with one another, the intercarpal ligaments, and the important transverse carpal ligament (flexor retinaculum) maintain a strong, fixed transverse carpal arch. Projecting distally from the central third of this arch are the fixed central metacarpals, the second and third. Littler called this the "the fixed unit of the hand". It forms a fixed transverse arch of carpal bones and a fixed longitudinal arch created by the anatomic convexity of the metacarpals. As a stable foundation, this unit creates a supporting base for the three other mobile units. This central beam moves as a unit at the wrist under the influence of the prime wrist extensors (the extensor carpi radialis longus and brevis) and the prime wrist flexor, the flexor carpi radialis. These major wrist movers insert on the second and third metacarpals. Thus, the fixed central unit is positioned for activity of the adaptive elements of the hand around it.

The distal row of carpal bones constitutes a fixed transverse arch. At the level of the metacarpal heads, the transverse arch of the hand becomes mobile, which is possible because the first metacarpal moves through a wide range of motion at the saddle-like carpometacarpal joint. The loose capsular ligaments and the shallow saddle articulation between the first metacarpal and the trapezium allow circumduction of the mobile first metacarpal. Its range of motion is checked by these capsular ligaments, including the volar beak ligament, and by its attachment to the fixed hand axis through the adductor pollicis, the first dorsal interosseous, and the fascia and skin of the first web space. The mobile fourth and fifth metacarpal heads move dorsally and palmarly in relation to the central hand axis by limited mobility at the carpometacarpal joints. These metacarpal heads are tethered to the central metacarpals by the intermetacarpal ligaments. The latter unite adjacent metacarpophalangeal volar plates, which are an intimate part of the joint capsules.

When the head of the first metacarpal is palmar-abducted by thenar muscles innervated by the median nerve, and the



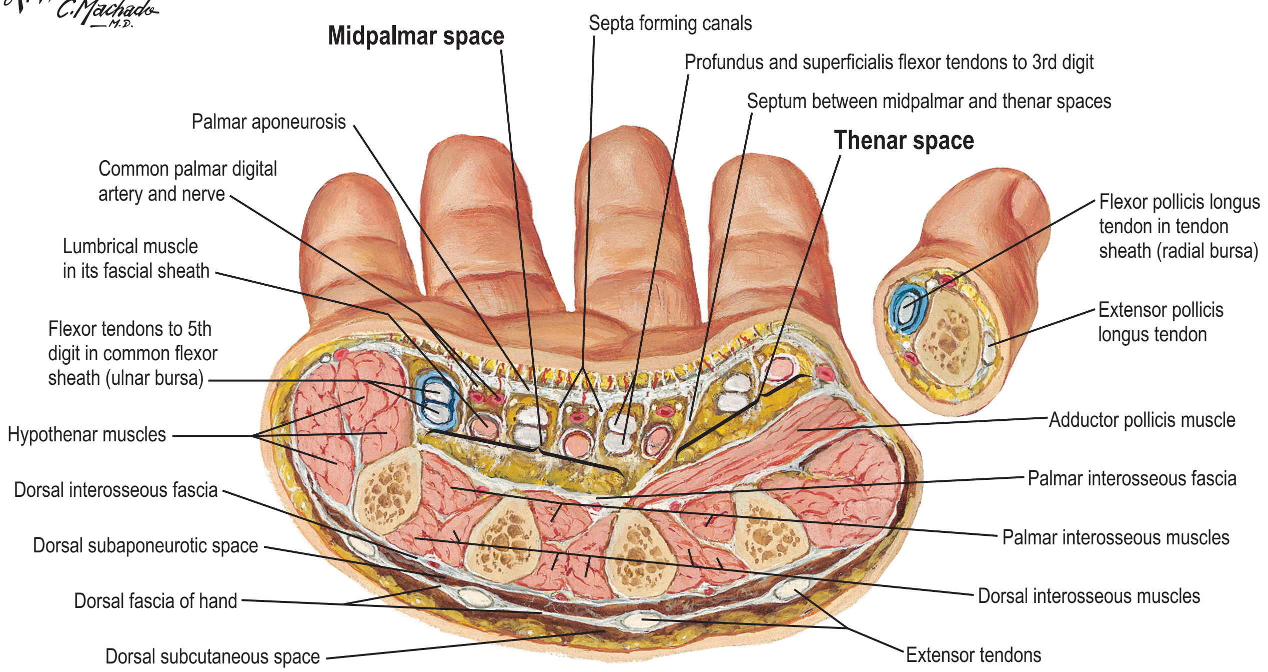


Fig. 1.5 These deep palmar and midpalmar axial views of the hand reinforce the concept of distinct anatomic compartments separated by fascia. *(Reprinted with permission from www.netterimages.com © Elsevier Inc. All Rights Reserved.)*

fourth and fifth metacarpals are palmar-abducted by the hypothenar muscles innervated by the ulnar nerve, a volar, concave, transverse metacarpal arch is created, approximating a semicircle. The mobile metacarpal heads are pulled dorsally by extrinsic extensor tendons when the thenar and hypothenar muscles relax. It is obvious that a flaccid paralysis of the intrinsic muscles of the hand in median and ulnar nerve palsy will produce a flattened or even reversed transverse metacarpal arch. The active production of a semicircular transverse arch by the thenar and hypothenar muscles creates the proper circumferential arrangement of the metacarpophalangeal joints for convergence of the fingers in flexion. In this position the fingers, flexing at the metacarpophalangeal joints only, converge, forming with the thumb a cone, the apex of which lies over the anatomic center of the hand (Fig. 1.8). A vertical line dropped from the apex of the cone to the center of its base will strike the third metacarpophalangeal joint. This point at the apex of the transverse metacarpal arch is the anatomic center of the hand. With the fingers fully abducted, the tips form radii of equal length from the anatomic center of the hand. The same radius projected proximally falls at the wrist joint.

The most important single motor operating the central hand beam at the wrist level is the extensor carpi radialis brevis, which works against gravity, positioning the pronated hand into extension. In the absence of any other motors it pulls the central third metacarpal into extension, making it the apex of the passively created transverse metacarpal arch.

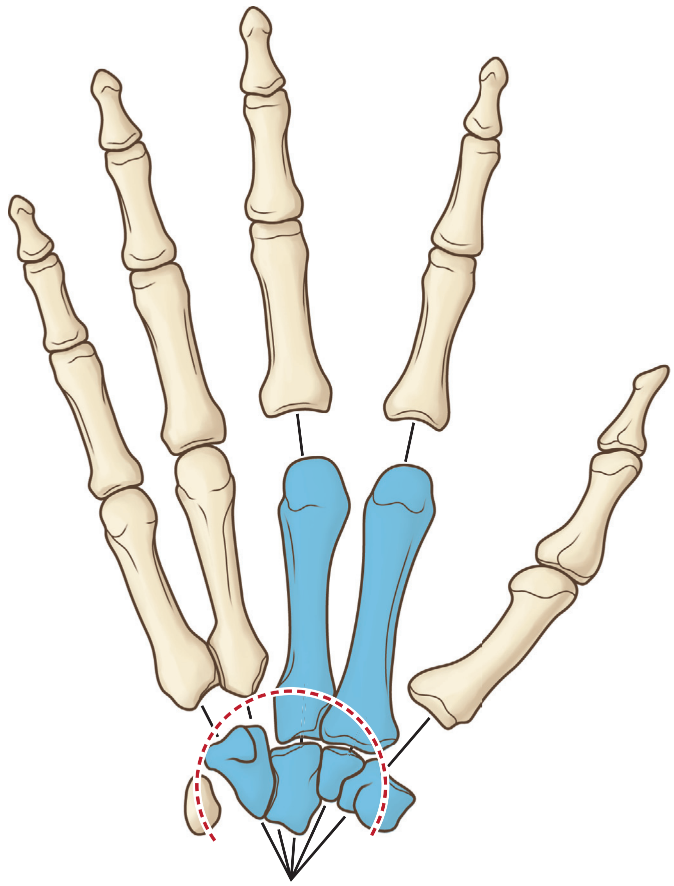


Fig. 1.7 Exploded view of the functional elements of the hand: (1) the thumb and its metacarpal with a wide range of motion at the carpometacarpal joint; (2) the index digit with independence of action in several planes; (3) the third, fourth, and fifth digits with the fourth and fifth metacarpals; and (4) the fixed unit consisting of the carpals with the fixed transverse carpal arch and the second and third metacarpals forming a fixed longitudinal arch. *(Redrawn after McCarthy JG.* Plastic Surgery. *Philadelphia: WB Saunders, 1990.)*

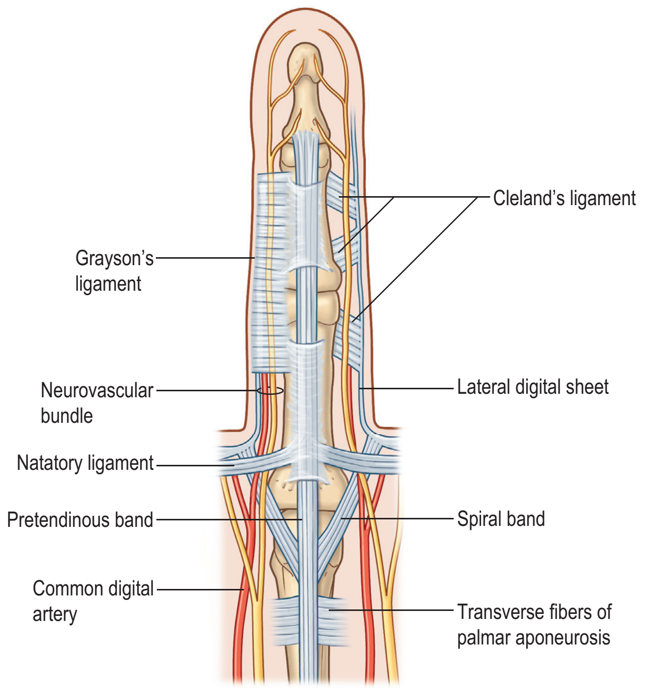


Fig. 1.6 The components of the digital fascia that help to anchor the axial plane skin are Grayson's ligaments palmar to the neurovascular bundles and Cleland's ligaments dorsal to the bundles. *(Redrawn after McCarthy JG.* Plastic Surgery. *Philadelphia: WB Saunders, 1990.)*

The wrist

The wrist joint is the site for major postural change between the arm beam and the working hand end piece (Fig. 1.9). It has a multiarticulated architecture that creates a potentially wide range of motion in flexion, extension, radial deviation, ulnar deviation, and circumduction. The distal radioulnar joint allows pronation and supination of the hand as the radius rotates around the head of the ulna. The proximal row of carpal bones (scaphoid, lunate, triquetrum, pisiform) articulates with the distal radius and ulna, providing the ability to flex and extend the hand and perform radial and ulnar deviation. The distal carpal row (trapezium, trapezoid, capitate, and hamate), along with the second and third metacarpals, forms the "fixed unit" of the hand.

The radiocarpal joint includes the carpal bones and the distal radius (Fig. 1.10). The principal articulation of the carpus is with the distal surface of the radius. The articular surface of the radius slopes in several planes. In the radial-to-ulnar plane, the radius exhibits an average slope of 22°. In the dorsal-to-palmar plane, the articular surface of the radius slopes 12° with the dorsal surface more distal than the palmar surface. Fractures of the distal radius frequently result in a loss of the normal radiocarpal configuration in one or both planes. A loss

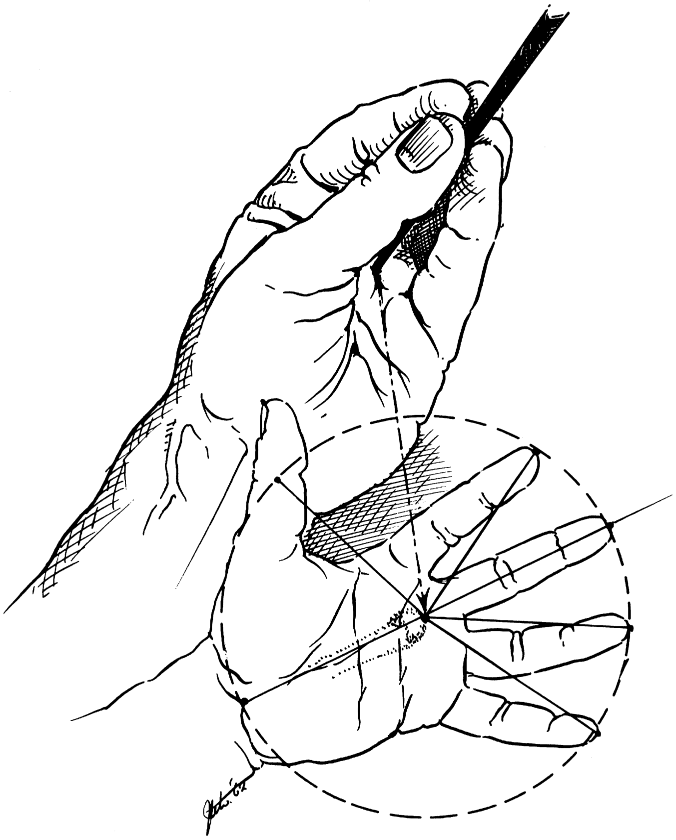


Fig. 1.8 When the adaptive arch is semicircular, the fingers converge in a cone over the anatomic center of the hand – the long-finger metacarpophalangeal joint. *(From McCarthy JG.* Plastic Surgery. *Philadelphia: WB Saunders, 1990.)*

of the normal dorsal-to-palmar tilt of the articular surface will result in a change in the biomechanical properties of the wrist joint, which may lead to degenerative arthritis.

The relationship of the length of the radius to the length of the ulna is fairly constant in individuals, and is termed ulnar variance. The distal ulna will complete the curve of the articular surface of the radius. If the end of the ulna falls short of this curvature, the condition is termed ulnar negative variance. If the ulna extends distal to this imaginary extension, the condition is termed ulnar positive variance. Either condition may lead to wrist problems. Ulnar negative variance is associated with a higher incidence of Kienböck's disease, avascular necrosis of the lunate. Ulnar positive variance greater than 2–3 mm is associated with ulnar impaction (Fig. 1.11).

Gilula and others have described several anatomic features that denote normal extracarpal and intracarpal architecture.[26] A line that follows the proximal articular contours of the proximal row of carpal bones circumscribes a smooth arc, termed the greater arc (Fig. 1.12). A disruption in the smooth appearance of this arc is one of the signs of carpal abnormality, such as abnormal rotation of one of the bones of the proximal carpal row, as would be seen with disruption of the scapholunate ligament. Similarly, the joint line between the proximal and distal row of carpal bones circumscribes another smooth arc, termed the lesser arc. The presence of abnormalities in either of these arcs may be an indication of carpal pathology, either acute or chronic.

The scaphoid and lunate bones of the proximal carpal row form the convex articular counterparts of the concave distal radius for the major wrist articulation. In fact, the articular surface of the radius is divided into scaphoid and lunate fossae (Box 1.2). The triquetrum articulates with the lunate in the proximal row, and with the hamate across the midcarpal

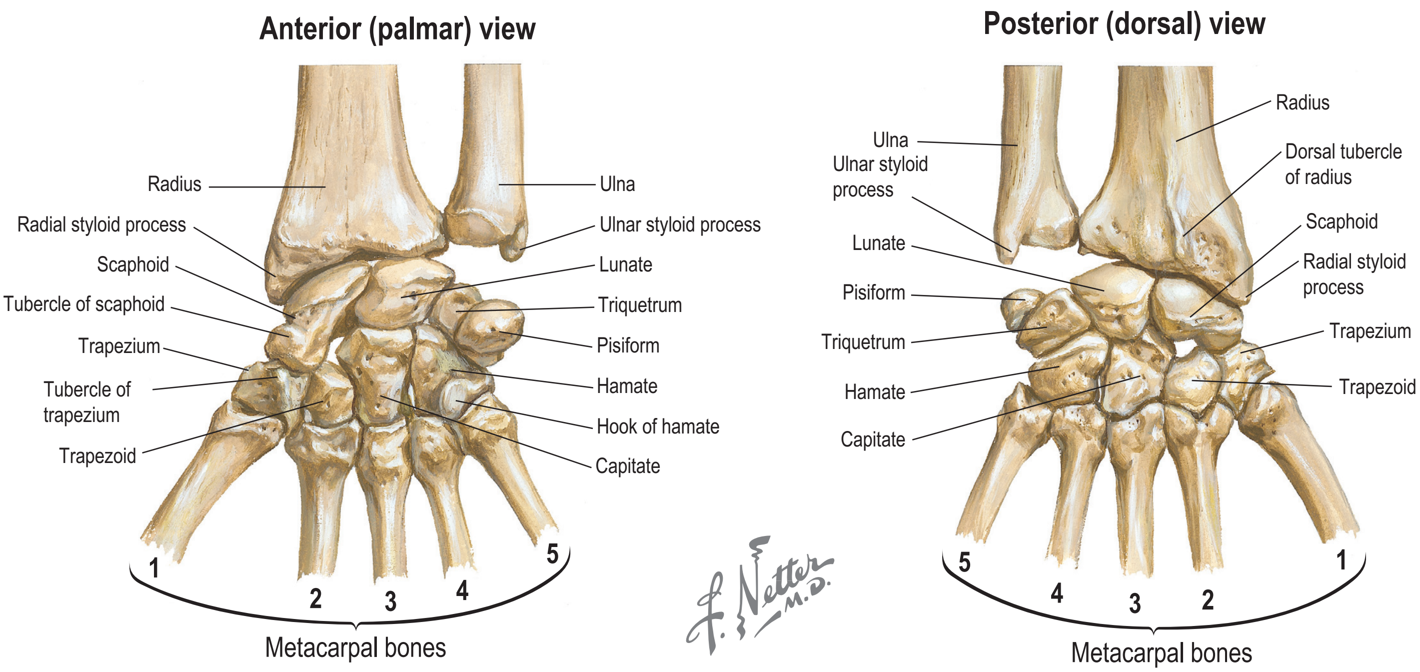


Fig. 1.9 Palmar **(A)** and dorsal **(B)** views of the bones of the wrist. *(Reprinted with permission from www.netterimages.com © Elsevier Inc. All Rights Reserved.)*

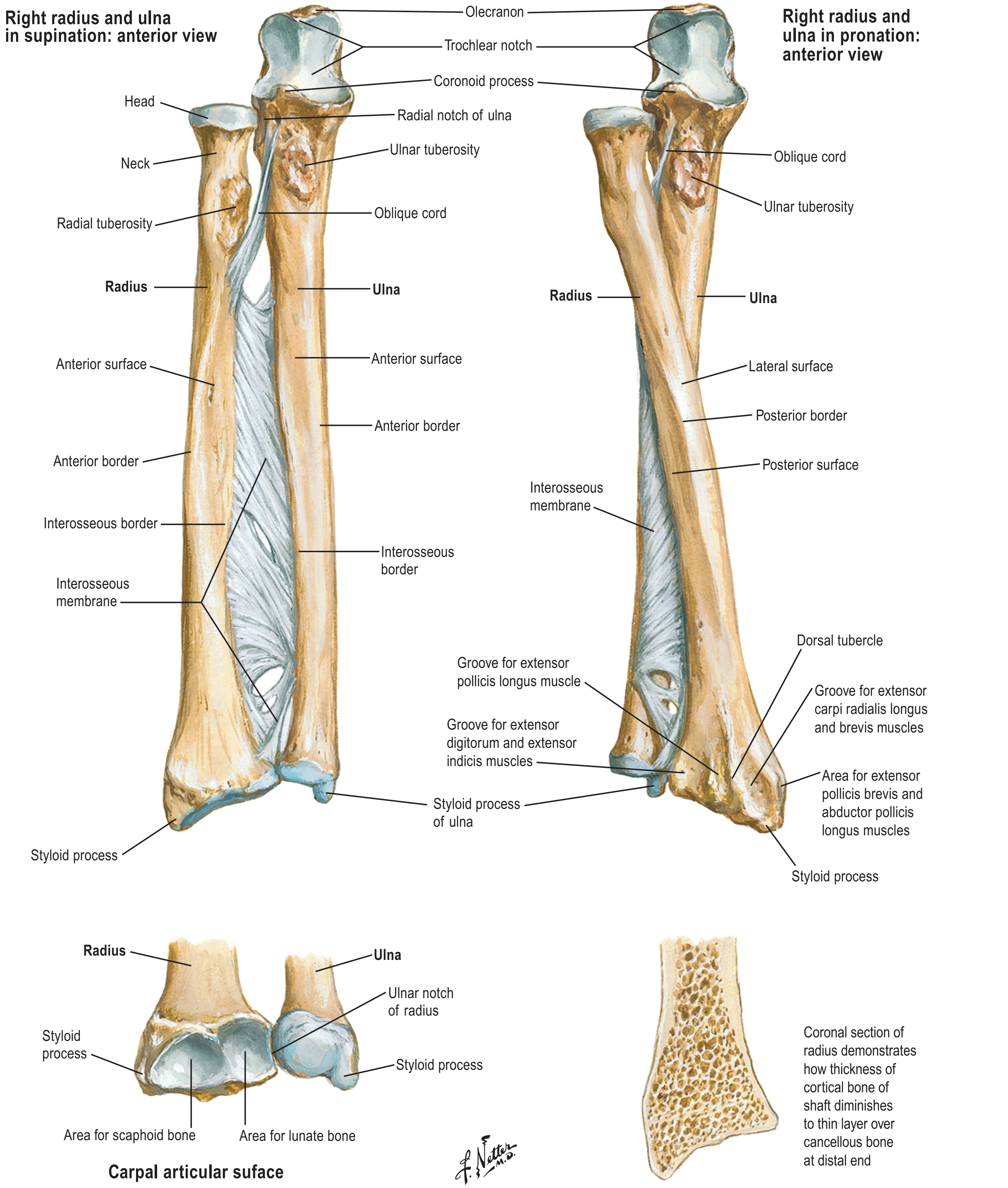


Fig. 1.10 Relationship of the radius and ulna at the proximal and distal radioulnar joints. *(Reprinted with permission from www.netterimages.com © Elsevier Inc. All Rights Reserved.)*

Fig. 1.11 X-ray of ulnar positive variance: this patient has ulnar-sided wrist pain due to ulnar impaction syndrome.

joint. The pisiform is essentially a floating bone, unimportant for carpal stability.

All four of the bones in the distal carpal row present articular surfaces for junction with the metacarpals. The distal carpal row forms a solid architectural arch with the central capitate as the keystone. The nature of the articulations of the distal carpals with one another, and of the carpal ligament (flexor retinaculum), is such that they make up a strong and fixed transverse carpal arch (Box 1.3).

The complex motions of the wrist are a product of the sums of the movements of the carpal bones in various planes and degrees of rotation relative to one another. The motion of any one carpal bone is a consequence of several factors. The first factor is the contour of the bone and the arrangements of its articular surfaces. The second is the degree of freedom afforded by intrinsic ligaments, which are ligaments originating from one carpal bone and inserting on another carpal bone, and by extrinsic ligaments, which are ligaments arising from the radius or ulna and attaching to a carpal bone or bones. This complex set of ligaments and the shape of the intercarpal and radiocarpal articulations control movement because no muscles arise or insert on any of the carpal bones except for the pisiform.

This unique adaptation of nature avoids the need for a thickly muscled wrist and hand unit. It permits great flexibility in positioning the hand in space without the need for sets of muscle agonists and antagonists to control the several degrees of freedom of movement.

The proximal row of carpal bones is anchored to the radius by a series of stout palmar ligaments arising primarily from the radius and by an additional set of stout ligaments arising from the ulna and the palmar portion of the triangular fibrocartilage complex. The triangular fibrocartilage complex separates the distal end of the ulna from the ulnar-sided carpal bones and serves to suspend the distal ulna to the radius at the distal radioulnar joint. These primary extrinsic palmar ligaments take the form of an inverted "V" with its apex pointed distally.

The three most predominant nerves innervating the triangular fibrocartilage complex are the dorsal cutaneous branch of the ulnar nerve (100%), the medial antebrachial cutaneous nerve (91%), and the volar branch of the ulnar nerve (73%). Other nerves play a minor role in the innervation of the triangular fibrocartilage complex: the anterior interosseous nerve, the posterior interosseous nerve and the palmar branch of the median nerve.[28]

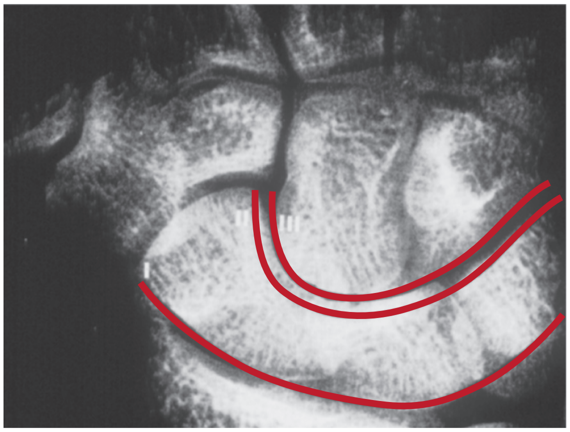


Fig. 1.12 Gilula's lines showing the greater arc and lesser arc of the carpal bones. *(Reproduced from Hentz VR, Chase RA.* Hand Surgery: A Clinical Atlas. *Philadelphia: WB Saunders, 2001.)*

BOX 1.2 **Clinical pearl: blood supply to the scaphoid**

Investigations by Gelberman and Menon have described two main vessel systems that perfuse the scaphoid via ligamentous attachments.[27] The superficial palmar branch of the radial artery contributes a volar blood supply that feeds the distal scaphoid. The dorsal carpal branch of the radial artery contributes a dorsal blood supply that also primarily feeds the distal scaphoid. Therefore, the proximal scaphoid is poorly vascularized and is susceptible to nonunion after proximal pole fracture.

BOX 1.3 **Clinical pearl: checking for malrotation**

The tubercle of the scaphoid is found at the distal flexion crease of the wrist joint, lateral to the tendon of the flexor carpi radialis. It is an important skeletal landmark in evaluating digital malrotations. Normally, each finger points to the scaphoid tubercle when individually flexed. A finger that points away from the tubercle may do so because of destructive flattening of the carpal arch. More commonly, it may result from malrotation following a metacarpal or phalangeal fracture (Fig. 1.13).

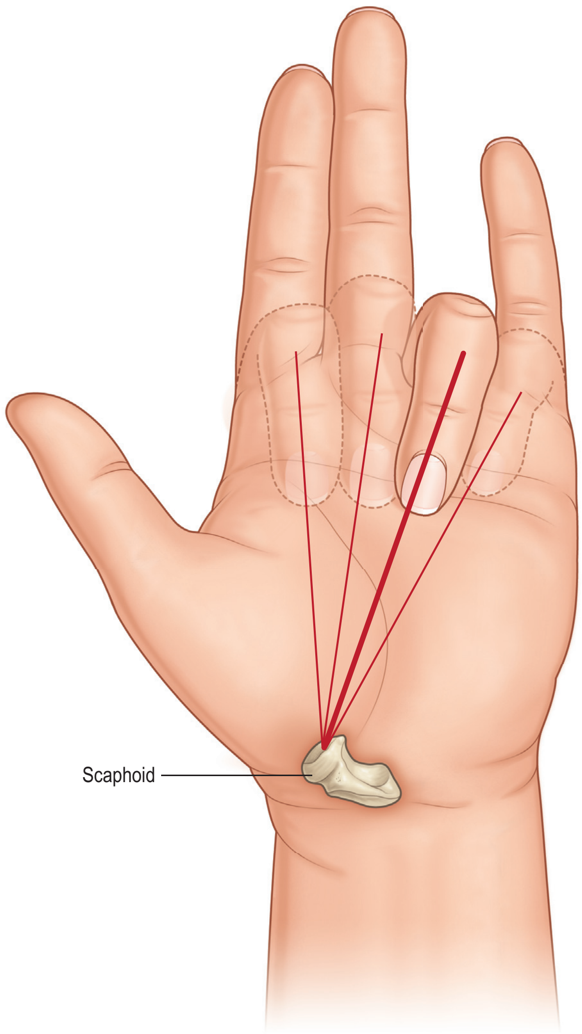


Fig. 1.13 Each finger in correct alignment points to the tubercle of the scaphoid when flexed individually. *(Redrawn after Chase RA.* Atlas of Hand Surgery, *vol. 1. Philadelphia: WB Saunders, 1973.)*

Dorsally, the extrinsic radiocarpal ligament complex is thinner and is primarily a condensation of capsular tissues, except for two stout structures, the dorsal intercarpal ligament joining the distal pole of the scaphoid and the triquetrum, and the dorsal radiocarpal ligament. According to work by Viegas, these two dorsal ligaments form a unique lateral "V" configuration that allows variation in length by changing the angle of the "V" while maintaining a stabilizing force on the scaphoid during wrist range of motion.[29]

The intrinsic ligaments are broad, stout structures that link one carpal bone to another, either within the proximal or distal row, or linking one carpal row to the other. The two most significant intrinsic ligaments are the scapholunate ligament and the lunotriquetral ligament. The scapholunate ligament anchors the scaphoid to the lunate to allow these two carpal bones to move in synchrony. Berger has subdivided this U-shaped structure into three regions: dorsal, proximal, and palmar.[30] The dorsal region is thick and controls scapholunate stability. The proximal portion, composed mainly of fibrocartilage, and the palmar region, with thin and obliquely oriented fibers, are less important for stability.[31] The lunotriquetral ligament is also composed of dorsal, proximal, and palmar portions. There is less motion between these two carpal bones. Disruption of either the scapholunate or lunotriquetral ligaments may lead to wrist instability as the normal restraints on synchronous motion are removed.

Joint motion

The bony anatomy of the hand is presented in Fig. 1.14. Normal metacarpophalangeal joint motion in the fingers ranges from 0 to 90°. Lateral activity in the metacarpophalangeal joints is limited by the rein-like collateral ligaments. These ligaments are loose and redundant when the metacarpophalangeal joints are in extension, allowing maximal medial and lateral deviation. As the metacarpophalangeal joint is flexed, the cam effect of the eccentrically placed ligaments and the epicondylar bowing of the collateral ligaments result in tightening and strict limitation of lateral mobility (Fig. 1.15). The fingers that have been fixed in extension during a period of healing have had the stage set for collateral ligament shrinkage and locking of the metacarpophalangeal joints in hyperextension.

The proximal interphalangeal joint can be pushed to 110° of flexion, but extension usually cannot be carried beyond 5° of hyperextension because of the ligamentous volar plate, which is an inseparable part of the joint capsule. The medial and lateral collateral ligaments are a part of the capsule. They are radially fixed in a manner that allows no medial or lateral deviation of the joint in any position. The shape of the articular joint surface also strongly contributes to this stability in lateral motion.

The distal interphalangeal joints of the fingers can be pushed into about 90° of flexion before they are limited by the dorsal joint capsule and extensor mechanism. The distal interphalangeal joints extend to 30° of hyperextension. There is no lateral mobility in these joints with the collateral ligaments intact. The collateral ligaments of the distal interphalangeal joints are simply thickened medial and lateral portions of the joint capsule.

Biomechanical concept: joint motion

Brand and Hollister, in their textbook, *Clinical Mechanics of the Hand*, discuss how joints move.[32] An axis of rotation of a joint refers to a line fixed to the proximal bone about which the motion of the distal bone appears to be a pure rotation. For the simple (hinge type) interphalangeal joints of the fingers, the motion occurs only in flexion and extension; the axis of rotation is perpendicular to the sagittal plane and is located in the distal head of the phalanx proximal to the joint. A related concept is that of the degrees of freedom of a joint. The degrees of freedom of a joint are the minimum number of axes of rotation that can be used to describe completely the motion of the bone distal to the joint. The wrist as a whole, for example, has two degrees of freedom (flexion–extension and radial–ulnar deviation), represented by two nearly perpendicular axes of rotation.[33] The kinematics of more complex joints such as the thumb carpometacarpal joint[34] or the intercarpal joints[35] is still the subject of research and thought to have at least two degrees of freedom with nonintersecting, nonperpendicular axes of rotation.

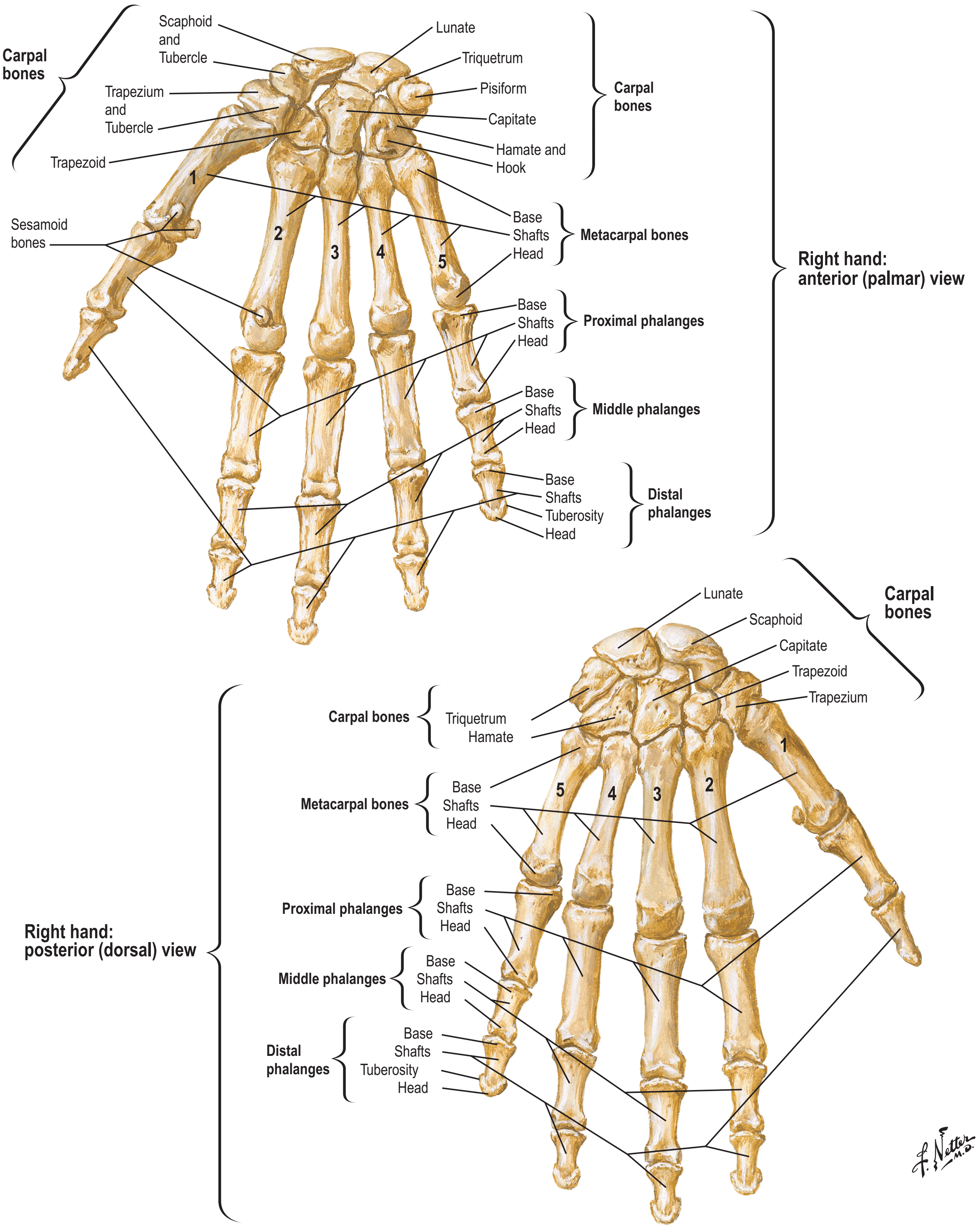


Fig. 1.14 Bony anatomy of the wrist and hand. *(Reprinted with permission from www.netterimages.com © Elsevier Inc. All Rights Reserved.)*