51

c00051
Compartment Syndrome and Volkmann Ischemic Contracture

Milan V. Stevanovic and Frances Sharpe

s0010 p0010 *Acknowledgment: The authors gratefully acknowledge the contributions of Dr. Ayan Gulgonen and Dr. Kagan Ozer, who wrote the chapter on compartment syndrome that appears in the sixth edition of* Green's Operative Hand Surgery.

p0020 These videos may be found at *ExpertConsult.com:*

o0010 **51.1** Surgical technique of upper extremity fasciotomy, cadaver demonstration.

o0015 **51.2** Ten-year follow-up on flexor origin slide for "moderate"-type Volkmann contracture.

o0020 **51.3** Eighteen-month follow-up on functional free muscle transfer for finger flexion for "severe"-type Volkmann contracture.

s0015 COMPARTMENT SYNDROME

p0040 Acute compartment syndrome (ACS) of the extremity is a diagnosis requiring emergent surgical intervention. It is characterized by sustained elevation of tissue pressure within an osseofascial or fascial compartment that exceeds tissue perfusion pressure. This results in local circulatory impairment, ischemia, cellular anoxia, and ultimately tissue death. ACS represents the acute phase of the injury during which time surgical intervention can reduce the extent of irreversible muscle injury. Timely diagnosis and treatment are critical in reducing the extent of permanent changes within muscle and nerve tissue. Even with emergent treatment, there may be permanent disability in the affected extremity and a subsequent need for additional surgery, including amputation.[22] Volkmann ischemic contracture represents the late sequelae of compartment syndrome. This disorder has a spectrum of fixed muscle contractures and muscular and neurologic impairments. Numerous authors have contributed to our understanding and treatment of this condition. Table 51.1 summarizes some of the historical events in the recognition of this entity, its etiology, its pathologic findings, and its sequelae.

s0020 Types of Compartment Syndromes

s0025 Acute Compartment Syndrome

p0045 Acute compartment syndrome (ACS) occurs when tissue pressures rise high enough within an osseofascial compartment to cause tissue ischemia. The resultant tissue injury can range from reversible muscle swelling to permanent tissue necrosis depending on the magnitude and duration of tissue pressure elevation. When pathologic tissue pressure elevation has been present for less than 4 hours, ACS is in the early stage[39]; when pathologic tissue pressure elevation has been present for more than 4 hours, ACS is in the late stage.

Impending Compartment Syndrome s0030

Impending compartment syndrome represents a clinical setting p0050 in which a compartment syndrome is at risk of developing; however, tissue pressure is not yet sufficiently elevated to cause muscle ischemia. Clinical scenarios in which this may occur include limb reperfusion after prolonged ischemia, posttraumatic swelling of a limb, or high-energy injuries.

Exercise-Induced or Exertional Compartment Syndrome s0035

Exercise-induced compartment syndrome is a reversible tissue p0055 ischemia due to a noncompliant fascial compartment that is unable to accommodate muscle expansion occurring during exercise. It has been described in both the upper and lower extremities and is different from ACS in that the symptoms are reversible after cessation of exercise. Emergent surgery is not usually indicated.[10,90] Both traditional fasciotomy and endoscopically assisted fasciotomy have been used to treat exercise-induced compartment syndrome.

Crush Injury or Crush Syndrome s0040

Crush injury is the external compression of an extremity, as p0060 might occur in a building collapse or construction injury or in an obtunded patient who lays on an extremity for a prolonged period. The compression of the extremity leads to muscle ischemia and reperfusion injury as the compression is relieved. This process of events can lead to compartment syndrome. *Crush syndrome* is a localized crush injury with systemic manifestations. Reperfusion of the affected extremity can rapidly release muscle breakdown products into the system, which can lead to renal failure or death.[13]

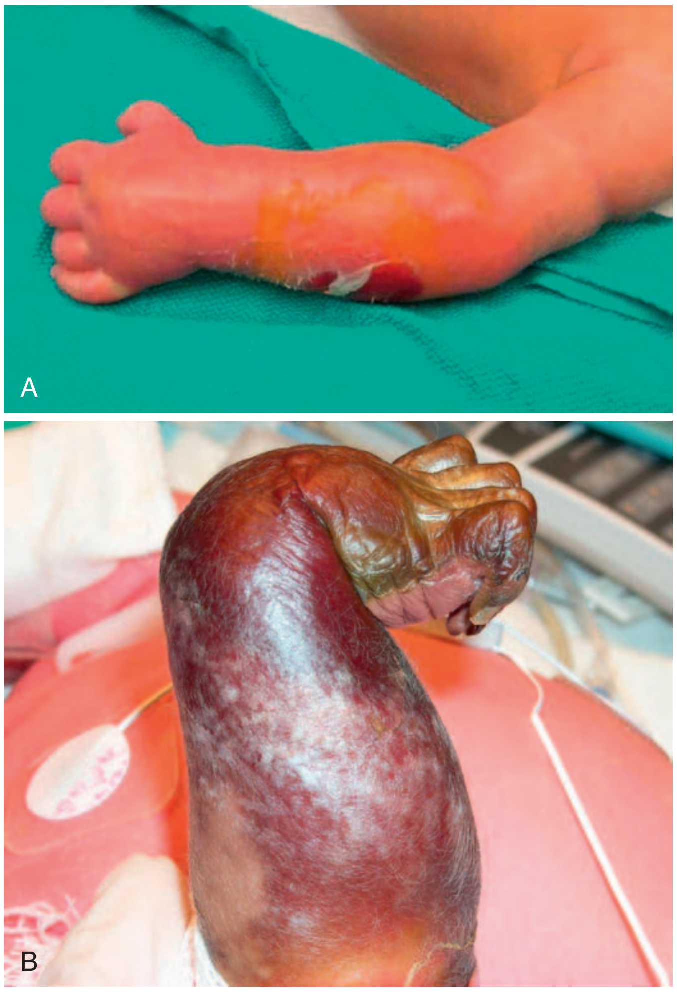
Neonatal Compartment Syndrome and Neonatal Volkmann Contracture s0045

Both neonatal compartment syndrome and neonatal Volkmann p0065 contracture have been reported. Awareness of this diagnosis is important because early recognition and treatment can improve the functional outcome and growth in neonatal compartment syndrome. In addition to swelling of the forearm, there is often a characteristic skin lesion on the proximal lateral arm, known as the *sentinel lesion of neonatal compartment syndrome.*[66]

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051

t0010 **TABLE 51.1 Events in the Recognition and Understanding of Compartment Syndrome**

Author and Year	Development
Volkmann, 1881[87a]	First thorough description of this entity with attribution of the cause to muscle ischemia
Leser, 1884[41a]	Animal investigations; concluded that the pathologic findings were a result of oxygen deprivation
Hildebrand, 1890[45a]	First to use the term *Volkmann's contracture*; now sometimes referred to as *Volkmann-Leser contracture*
Bardenhauer, 1906[4a]	Release of internal pressure through a forearm fasciotomy to treat an impending Volkmann contracture
Brooks, 1922, 1925[9a,9b]; Jepson, 1926[45a]	Animal model used to reproduce compartment syndrome through vascular occlusion; muscle necrosis could be prevented by surgical decompression of the muscle compartment
Griffiths, 1940[35a]	Emphasized arterial injury and reflex spasm of the collateral vessels as the sole source of muscle ischemia; minimized the role of tight external dressings as the cause of muscle ischemia
Seddon, 1956[74] and 1964[73]	Described the pattern of muscle infarction common in compartment syndrome (ellipsoid infarct) and treatment with infarct excision; also highlighted the importance of ischemic injury to nerves
Holden, 1975, 1979[41b,42]	Reestablished both intrinsic and extrinsic causes of muscle ischemia; distinguished two patterns of injury leading to muscle ischemia: Type 1: Arterial insult proximal to the site of ischemia Type 2: Elevated intrinsic pressure within the compartment from either internal or external sources
Matsen, 1975[57]	Unified concept of compartment syndrome
Whitesides, 1975[89]	Tissue pressures as a determinant of the need for fasciotomy



f0010 **FIGURE 51.1** **A,** Neonatal compartment syndrome. Note the hallmark sentinel lesion at the lateral proximal forearm. **B,** Neonatal Volkmann contracture. The entire forearm is necrotic. This patient underwent amputation at the proximal forearm. (**A,** See Ragland RI, Moukoko D, Ezaki M, et al: Forearm compartment syndrome in the newborn: report of 24 cases. *J Hand Surg [Am]* 30(5):997–1003, 2005.)

Established neonatal Volkmann contracture cannot be improved by early intervention; however, awareness of this diagnosis can aid in counseling of the family and treatment of the patient (Figure 51.1, *A* and *B*).

s0050 **Volkmann Ischemic Contracture**

p0070 Volkmann ischemic contracture is the end result of prolonged ischemia, is associated with irreversible tissue necrosis, and has a spectrum of presentations.

s0055 Etiologic Findings and Incidence

p0075 Compartment syndrome in the upper extremity is most commonly associated with trauma. A variety of conditions and injuries can lead to ACS. These include fractures, penetrating trauma, closed soft tissue injuries, infection, animal and insect bites, extravasation injuries, ischemia-reperfusion injury, external compression by tight dressings or casts, burns, or crush injuries. Compartment syndrome in the absence of fracture should raise concern about an underlying bleeding disorder (Figure 51.2).

p0080 The incidence of upper extremity compartment syndrome is difficult to determine. The estimated incidence in pediatric upper extremity fractures is approximately 1%.[36] In a large series of trauma patients, the incidence of fasciotomy associated with all upper extremity traumas was 0.41%. Branco and colleagues[9] noted a decreasing incidence of the need for surgical fasciotomy over a 10-year period, despite stable injury severity scores, with the overall incidence for upper and lower extremity trauma decreasing from 3.2 to 0.7%. They suggested a possible explanation for the declining incidence as the diminished use of crystalloid for fluid resuscitation and the use of mannitol to decrease extracellular fluid volume. Fasciotomy rates associated with traumatic arterial injury ranged from 6.7 to 16%.[30,83]

Historically, ACS of the upper extremity in the pediatric population was most commonly reported in association with supracondylar humerus fractures. Likely, this was related to the historical treatment methods of casting with the elbow in a position of hyperflexion. Currently, pediatric fracture patterns most associated with forearm compartment syndrome are both-bone forearm fractures and supracondylar humerus fractures associated with distal radius fractures (i.e., floating elbow p0085

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051

f0015


FIGURE 51.2 This 4-year-old presented with hand and forearm swelling after minor trauma. Other areas of bruising were noted. After workup, the child was found to have hemophilia A. He underwent fasciotomy of his hand and forearm. **A,** Swelling of the hand and forearm. **B,** After dorsal fasciotomy of the hand and volar extended carpal tunnel release and forearm fasciotomy. **C,** Bruising of the periorbital region.

injury).[6,36,46,93] In adults, the most common upper extremity fractures associated with compartment syndrome are distal radius fractures and both-bone forearm fractures.[25,46]

p0090 Compartment syndrome is more prevalent in males younger than 35 years of age, penetrating trauma, open fractures, elbow dislocations, and vascular injuries.[9,25,58] The need for surgical fasciotomy increases dramatically when vascular injury is present.[22,30] Compartment syndrome in the hand is most commonly associated with intravenous injections.[63]

s0060 Pathophysiologic Findings

p0095 The pathophysiology of ACS is complex. Several theories and models have been developed. The common prerequisite is a soft tissue structure (usually fascia) that prevents muscle expansion when the muscle is exposed to increased fluid volume. In all cases, the final common pathway is cellular anoxia.

p0100 Matsen presented a "unified concept" of compartment syndrome that incorporates several mechanisms of vascular compromise all leading to cellular injury.[57] Increased compartmental pressure occurring from either internal injury (edema, reperfusion, or bleeding) or external injury (tight cast or dressing, pressure garment) causes a decreased perfusion gradient between arteriole and venous pressures and a resultant decrease in local tissue perfusion. Decreased tissue perfusion results in further tissue insult, increased capillary leakage, and further increase in intracompartmental pressure. This causes a vicious cycle of increasing cellular ischemia leading to further capillary leakage and swelling and increasing compartment pressures (Figure 51.3).

p0105 Ongoing ischemia eventually leads to cell death and lysis of the myocyte. Degradative enzymes are activated and released into the interstitial tissues, causing further tissue necrosis. The extent of muscle injury depends on the duration of ischemia and the metabolic rate of the tissue. Prolonged ischemia can ultimately lead to liquefactive necrosis of the muscle compartment.

s0065 Diagnosis

s0070 Diagnosis of Acute Compartment Syndrome

p0110 The diagnosis of ACS is principally based on clinical examination. Maintenance of a high index of suspicion, particularly in

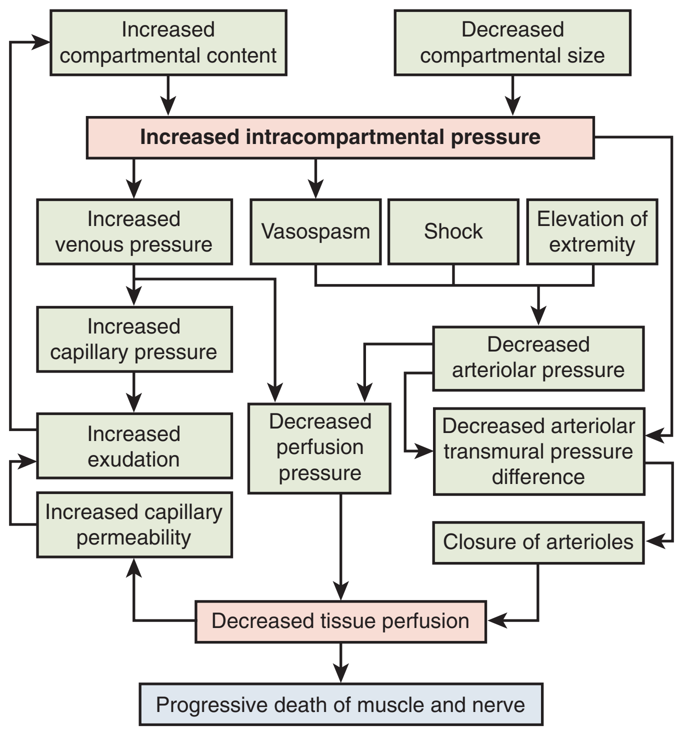


FIGURE 51.3 Schematic representation of factors contributing to the vicious cycle of compartment syndrome, based on the descriptions of Holden and the proposed unified concept theory of Matsen. (See Holden C: The pathology and prevention of Volkmann's ischaemic contracture. *J Bone Joint Surg Br* 61(3):296–300, 1979; and Matsen FA, 3rd: Compartmental syndrome: a unified concept. *Clin Orthop Relat Res* 113:8–14, 1975.) f0020

the setting of at-risk injuries and conditions, aids in the prompt recognition and treatment of this condition.

Although compartment syndrome is frequently associated with fractures, many other causes can also lead to ACS. Causes are commonly separated into intrinsic causes (typically, bleeding or swelling into a compartment) and extrinsic causes (applied external pressure preventing a compartment from expanding) (Box 51.1). The physician must keep this in mind because ACS not associated with fracture frequently has a delayed diagnosis and worse clinical outcomes.[43,65] p0115

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051

b0015 **BOX 51.1 Injuries That May Lead to Compartment Syndrome**

s0075 **Intrinsic Injuries**

p0120 High-energy fracture, usually in young male (open fractures more at risk than closed fractures)

p0125 Fracture in child

u0025 • Supracondylar fracture of humerus, especially one associated with distal radius fracture[6,44a]

u0030 • Both-bone forearm fractures (intramedullary nailing of pediatric both-bone and radial head fractures is associated with difficult reduction and prolonged tourniquet times[93])

p0140 Fracture in adult

u0035 • Distal radius fracture

u0040 • Upper extremity fractures associated with vascular injury

u0045 • Soft tissue trauma without fracture

u0050 • Blunt trauma without fracture or skin violation)

p0165 Penetrating trauma (usually from bleeding into otherwise closed compartment)

p0170 Vascular injury

u0055 • Trauma

u0060 • Iatrogenic procedures, such as venipuncture or arterial blood draw

u0065 • Reperfusion after prolonged ischemia

u0070 • Prophylactic fasciotomy should be considered after vascular repair[28,30]

p0195 Burns

u0075 • Edema associated with burn injury

u0080 • Electrical burns associated with deep muscle damage and edema

u0085 • Systemic inflammation and fluid resuscitation

u0090 • Burn eschar causes an extrinsic compression

p0220 Animal and insect bites (e.g., Crotalidae [pit viper] snakebite)

u0095 • Treatment of impending compartment syndrome from snakebite should be with antivenin

• (Crofab [ovine]; Antivenin Crotalidae Polyvalent ACP [equine]) u0100

• Rarely requires surgical decompression u0105

Intravenous fluid extravasation (hypertonic fluids such as intravenous contrast material) p0240

• Intraoperative fluid extravasation, particularly in patients where the arm position does not allow easy visualization of the extremity, and when infusion pumps are used[4b] u0110

Infection p0250

Bleeding disorders p0255

• Coagulation disorders (e.g., von Willebrand hemophilia) u0115

• Anticoagulation therapy u0120

• Spontaneous bleeding may occur with no trauma or minor trauma u0125

Extrinsic Injuries s0080

Compressive casts or dressings p0275

Burn eschar (circumferential inelastic eschar) p0280

• Important to release fingers with dermotomies if burn involves the hand u0130

Crush injury p0290

• In obtunded patient during drug or alcohol overdose u0135

• Resulting from coma, seizure, or hypoglycemic episode u0140

• Building collapse u0145

• Intraoperative positioning (prone or lateral positioning with poorly positioned axillary or chest roll causing axillary artery occlusion; also seen in the lower extremity with prolonged lithotomy position) u0150

p0315 The timing of presentation can vary from within the first few hours of injury to several days following injury.[70,76]

p0320 The hallmarks of diagnosis of ACS have classically been described as the six *P*s of compartment syndrome (Table 51.2): pain, pressure, paresthesias, pallor, paresis, and pulselessness. Some authors have added or substituted poikilothermia of the extremity as one of the *P*s. This use of the term *poikilothermia* is not completely accurate but indicates that the affected extremity is cool relative to body temperature. In most series, pain has been the earliest and most reliable finding. However, pain peaks at 2 to 6 hours of ischemia and then gradually subsides as muscle necrosis progresses and nerve function becomes impaired. Therefore, patients with a late presentation of or late diagnosis of compartment syndrome have less pain than those with an earlier presentation.

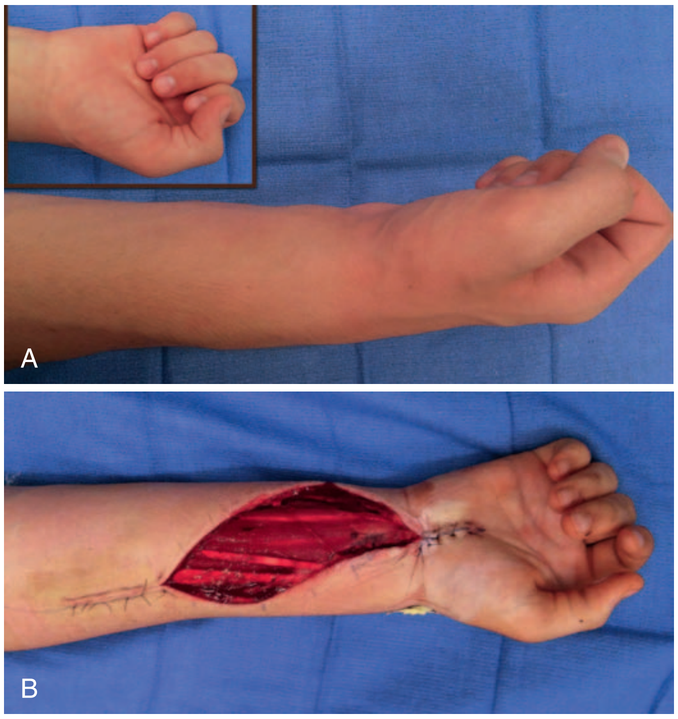
p0325 It has been suggested that in pediatric patients, "it's the *A*s, not the *P*s" that signal ACS.[49] These *A*s are an increasing requirement for analgesia, the presence of anxiety (or restlessness), and the presence of agitation (or crying).[3,49] Children are unable to articulate the feeling of paresthesias, and sensibility testing is unreliable.

p0330 Certain conditions can make the clinical diagnosis of ACS challenging. Altered levels of consciousness as can occur in head trauma, a medically induced coma, or obtundation from other causes can obscure the normal pain response that is one of the early signs of compartment syndrome. Similarly, distracting pain from polytrauma, neurologic injury in the affected limb, and/or regional anesthetic blockade can mask the signs and symptoms of compartment syndrome. Diagnosis is also more

TABLE 51.2 Diagnostic Findings in Compartment Syndrome t0015

Sign or Symptom	Description
Pain	Described as deep, constant, often poorly localized pain that is disproportionate to the physical findings; often poorly responsive to analgesics Pain is accentuated with passive stretching of the involved compartment. Although this is the most consistent and reliable finding, cases of "silent" compartment syndrome of the lower extremity have been reported (Badhe) and likely also occur in the upper extremity. Pain usually peaks at around 2 to 6 hours of ischemia and then subsides. Patients who present late with acute compartment syndrome may not report as much pain.
Pressure	Affected compartment(s) are firm and noncompressible; often described as "rock hard"
Paresthesias	Numbness or "pins-and-needles" sensation in the cutaneous distribution of the nerves that traverse the affected compartment
Pallor	Usually pale, but the extremity may also appear blotchy and often cool (see poikilothermia)
Paralysis	Late and unreliable finding. Muscle paralysis may be pain related. When true paralysis is present, this is a poor prognosticator for recovery.
Pulseless	Also usually a late finding and poor prognosticator for recovery

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051



f0025 **FIGURE 51.4** Localized compartment syndrome. This 16-year-old boy sustained a coronoid process fracture and a mildly angulated distal radius fracture through an old fracture malunion. He had pain and localized swelling at the distal forearm and subjective numbness in the median and ulnar distributions in the hand. His fingers were clenched and his thumb was flexed. He had pain with passive extension of the fingers. He underwent extended carpal tunnel release and fasciotomy. Compartment swelling was localized to the distal forearm. The proximal incision was closed at the time of primary surgery. Delayed primary wound closure was done after 4 days. **A,** Localized forearm swelling and clenched posture of the fingers and thumb. **B,** On postoperative day 2, persistent swelling of distal forearm musculature is present.

difficult in children and infants who may have difficulty in cooperating with examination, are nonverbal, or are apprehensive and crying. Also, the thicker layer of subcutaneous fat in children may contribute to a false sense of a soft compartment on palpation, further complicating the diagnosis. Diagnosis or exclusion of compartment syndrome on clinical grounds alone is often impossible.

p0335 If the clinician is uncertain of the diagnosis based on equivocal physical findings, compartment pressure can be measured (Figure 51.4 and Table 51.3). Several different methods can be used. Continuous pressure measurements can be obtained with a wick catheter or connection to a continuous pressure monitor.[59,89] Typically, the newer digital devices are used to assess or monitor the compartment.[7,21,38] These devices are sensitive to patient motion and should not supplant repeat clinical examinations. Although controversial, the thresholds/indications for fasciotomy are an absolute pressure greater than 30 to 40 mm Hg or pressures within 30 mm Hg of either the diastolic blood pressure or the mean arterial pressure.[79]

p0410 Although pulse oximetry of the affected extremity has not been found to be useful,[19,56] near-infrared spectroscopy (NIRS) may prove to be useful in the early diagnosis and monitoring of an impending compartment syndrome. This technique was proposed as a method of monitoring for compartment syndrome as early as 2001,[33] but it has not been widely adopted because of its cost and problems with availability of sensors and equipment. NIRS is noninvasive and capable of measuring the oxygenation state of at-risk tissues and may gain wider use in the future. NIRS is limited by the depth of tissue penetration (2 to 3 cm) and the presence of hematoma within the compartment.[20]

TABLE 51.3 Measurement of Compartment Pressures t0020

Aspect of Measurement	Considerations	
Patient position	Supine	u0155
	Measured extremity should be at heart level	u0160
	Measurements in uncooperative patients and children should be made with the patient sedated or in the operating room with the patient sedated	u0165
Needle	18-g straight, side-port, slit catheter, or wick	
Transducer	Handheld digital (Stryker pressure transducer)	u0170
	Arterial line monitor	u0175
Needle placement	Perpendicular to muscle belly	u0180
	Several readings at multiple depths	u0185
	Near fracture site (see Figure 51.4, localized compartment)	u0190
	Near area of maximum tension	u0195
Threshold pressure	30 to 40 mm Hg	u0200
	Within 30 mm Hg of diastolic blood pressure or mean arterial pressure	u0205
Contraindications to measuring compartmental pressure	Underlying neurovascular structures at risk	u0210
	Coagulopathy	u0215
	Diffuse cellulitis	u0220

In these questionable clinical situations, the safer intervention is to perform a fasciotomy. Bulging of the muscle compartment and clinical softening of the extremity at the time of fasciotomy confirms the diagnosis. p0415

Diagnosis of Exertional Compartment Syndrome s0085

Chronic exertional compartment syndrome of the upper p0420
extremity has been described in the flexor compartment of the forearm and in the anconeus muscle; in the hand, it has been described specifically in the adductor of the thumb.[2,8,35,51,78,80,81] Patients with chronic exertional compartment syndrome typically complain of pain that starts as a dull ache within the first 30 minutes after starting an activity. Burning, cramping, or aching pain progresses as the activity is continued. The pain escalates to a level of discomfort where the patient can no longer continue or where it adversely affects the patient's performance. Activities associated with exertional compartment syndrome of the upper extremity include sports such as rowing, bicycle riding, or motorcycle riding or repeated episodes of manual labor requiring a prolonged grip or pinch. The pain and tissue firmness resolve spontaneously with cessation of the activities. Diagnostic studies have principally involved measurement of compartment pressures before, during, and after exercise.[8,10,84] More recently, magnetic resonance imaging has been used before and after exercise as a diagnostic tool. A signal change in

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051

T2 imaging in an isolated fascial compartment associated with activity supports the diagnosis of exercise-induced compartment syndrome.[53]

s0090
PERTINENT ANATOMY

p0425 The compartments of the upper extremity are listed in Table 51.4. Any of these anatomic spaces can be affected by tissue pressure elevation. Although elevated tissue pressures are most commonly seen in osseofascial spaces, other tissue structures provide a rigid barrier that does not expand sufficiently to accommodate swelling. In the upper extremity, the fascial components and the skin can act as barriers that require decompression at the time of surgery.

s0095
Treatment

p0430 The goal of treatment is to prevent tissue necrosis, avert neurovascular compromise, and avoid permanent functional deficits. These devastating complications can be minimized or avoided with early recognition and prompt intervention.

p0435 The first step in treatment is to remove all possible extrinsic causes of pressure, including circumferential dressings, cast padding, and casts. Casts have been shown to restrict compartment expansion by 40%. Release of a cast and subsequent spreading reduces pressure elevation by 40 to 60% depending on the presence of dry or wet blood on the cast padding.[32] The limb should be elevated only to heart level. Although limb elevation may decrease swelling, it can also reduce perfusion to the affected limb, risking exacerbation of tissue ischemia.

p0440 A history of bleeding disorders or use of anticoagulation therapy should be obtained from the patient or family member. Laboratory analysis should include a complete blood count, prothrombin time, and partial thromboplastin time. If there is a suspicion of a bleeding disorder, a hematologist should be involved in the evaluation and treatment of the patient. Urinalysis for myoglobin, serum electrolytes, creatinine, and myoglobin should be obtained in the setting of prolonged ischemia, crush injury, or ischemia-reperfusion injury. Medical management of shock, hypoxia, metabolic acidosis, and electrolyte imbalance should be addressed immediately. Supportive care with vigorous hydration, correction of metabolic function, and treatment of hyperkalemia is necessary to prevent sequelae such as renal failure, shock, hypothermia, cardiac arrhythmias, or cardiac failure. Supportive care should be initiated in the emergency room but should not delay surgical treatment.

Hypertonic mannitol has been used to lower intracranial pressure. p0445 The use of mannitol in decreasing extremity swelling has been described in animal models and limited case studies. It has not gained widespread use for treatment of impending or acute compartment syndrome. Nonetheless, it has been hypothesized that the use of mannitol may have played a role in the decreased incidence of compartment syndrome in trauma patients at a single medical center over a 10-year time period.[9] Hypertonic mannitol has been found to decrease endothelial swelling and may help reduce muscle necrosis in its function as an oxygen-free radical scavenger.[62] In one clinical report, patients were given a 100-mL bolus of 20% mannitol, followed by an infusion of 10 g/hour for 6 to 24 hours.[11]

Emergent surgical decompression (fasciotomy, or release of p0450 the fascia overlying the affected compartments) performed as quickly and safely as possible is needed for ACS. Fasciotomy

t0025
TABLE 51.4 Compartments of the Upper Extremity

Compartments			Contents
Arm	Anterior		Biceps and brachialis muscles, brachial artery, and median nerve
	Posterior		Triceps muscle and ulnar and radial nerves
	Deltoid	Not technically a separate compartment but has a thick epimysium that may require decompression	
Forearm	Volar	Superficial	Flexor carpi radialis, palmaris longus, pronator teres, flexor carpi ulnaris, and flexor digitorum superficialis muscles
		Deep	Flexor digitorum profundus, flexor pollicis longus, pronator quadratus muscles,* and anterior interosseous nerve and artery
	Dorsal	Mobile wad	Brachioradialis, extensor carpi radialis longus, and extensor carpi radialis brevis muscles
		Extensor	Extensor digitorum communis, extensor carpi ulnaris, extensor pollicis longus, abductor pollicis longus, extensor pollicis brevis, and supinator muscles,† and posterior interosseous nerve
		Anconeus*	Anconeus
Hand	Thenar		Abductor pollicis brevis, opponens pollicis, and flexor pollicis brevis muscles
	Hypothenar		Abductor digiti minimi, flexor digiti minimi, and opponens digiti minimi muscles
	Adductor pollicis		Adductor pollicis muscle (two heads)
	Dorsal interossei (4)		Each is a separate compartment
	Volar interossei (3)		Each is a separate compartment
Fingers‡			

*Reported isolated involvement in exertional compartment syndrome.
†The supinator muscle is not typically a component of the extensor compartment, but decompression can be done through the brachioradialis/extensor carpi radialis longus interval.
‡Compression of the neurovascular structures by rigid Cleland and Grayson ligaments can lead to skin necrosis and/or loss of the finger.

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051

within the first 8 hours after diagnosis is associated with a lower risk of permanent functional impairment. Release of the epimysium surrounding the muscle may also be necessary. Necrotic tissue should be excised because it may become a nidus for infection or lead to subsequent fibrosis and contracture. Questionable tissue should be left in place for a second look at a later date. Late fibrosis of necrotic muscle can lead to compression of the adjacent nerves and further impair extremity function. Other concomitant procedures may be indicated based on the cause of the compartment syndrome, including fracture reduction and stabilization, vascular repair, and nerve exploration if indicated. Nerve repair or grafting should be performed at the time of definitive wound closure.

p0455 Late or delayed diagnosis increases the risk for severe complications, including infection, neurologic injury, need for amputation, and death. In the past, concerns about an increased risk of infection have led some authors to recommend not performing a fasciotomy after 24 hours has elapsed since the onset of symptoms. We do not feel this risk outweighs potential benefits and no longer consider this a contraindication for surgery. Currently, there are more options for wound management and antibiotic therapy. Removal of necrotic muscle can decrease the severity of subsequent muscle fibrosis and joint contracture. Débridement of nonviable muscle improves the environment for the neurovascular structures and may allow early functional reconstruction of the lost muscle(s) by means of tendon transfers or free functional muscle transfers (FFMTs).

p0460 In addition, the length of time that elevated pressure sufficient to cause tissue necrosis has been present is often unclear, and some muscle preservation may be facilitated with late fasciotomy. In some cases, good results in children have been reported following fasciotomy as late as 72 hours after the injury (within the acute swelling phase).[29] Dramatic, essentially full, recovery has been reported following compartment syndrome of the lower leg in children after delayed presentation.[15]

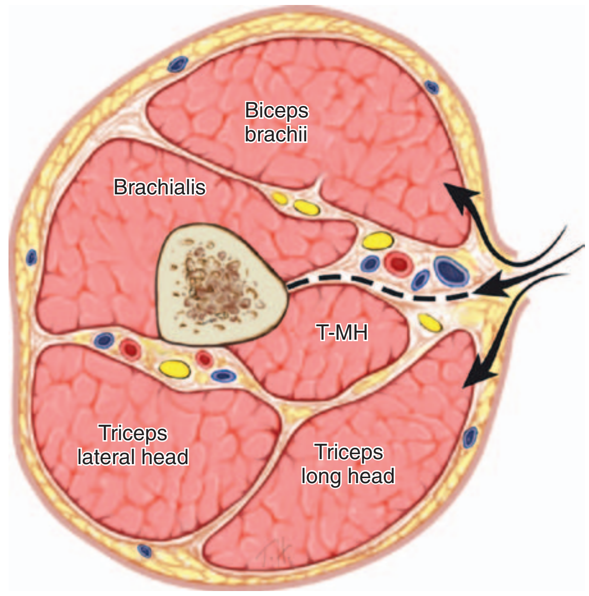
s0100 **Surgical Procedure**

s0105 ***Indications.*** The indications for surgical fasciotomy are described
p0465 previously. Our preference is to manage questionable cases of impending compartment syndrome with surgical decompression, provided the patient is stable enough for the procedure. Prophylactic fasciotomies should be performed following vascular repair/reconstruction where ischemia time exceeds 3 hours.[28] Shorter periods of ischemia do not eliminate the risk of developing compartment syndrome, and careful monitoring is necessary after vascular surgery.

s0110 ***Contraindications.*** Contraindications to fasciotomy are few.
p0470 Coagulopathy should be corrected prior to surgical intervention. Plasma, factor, or platelet transfusion may be necessary to optimize the patient for surgery. Intubated patients who are not stable for surgery should be considered for a bedside fasciotomy using local anesthesia and sedation.[26]

s0115 **❖ AUTHOR'S PREFERRED METHOD OF TREATMENT**

p0475 The surgical incision for the upper extremity is extensile from the brachium to the carpal tunnel. The extent of the release performed is tailored to the clinical and intraoperative findings. Release of the dorsal forearm and compartments of the hand requires separate incisions when indicated. A separate incision for a dermotomy of each of the fingers may also be added to prevent skin necrosis and loss of the fingers.



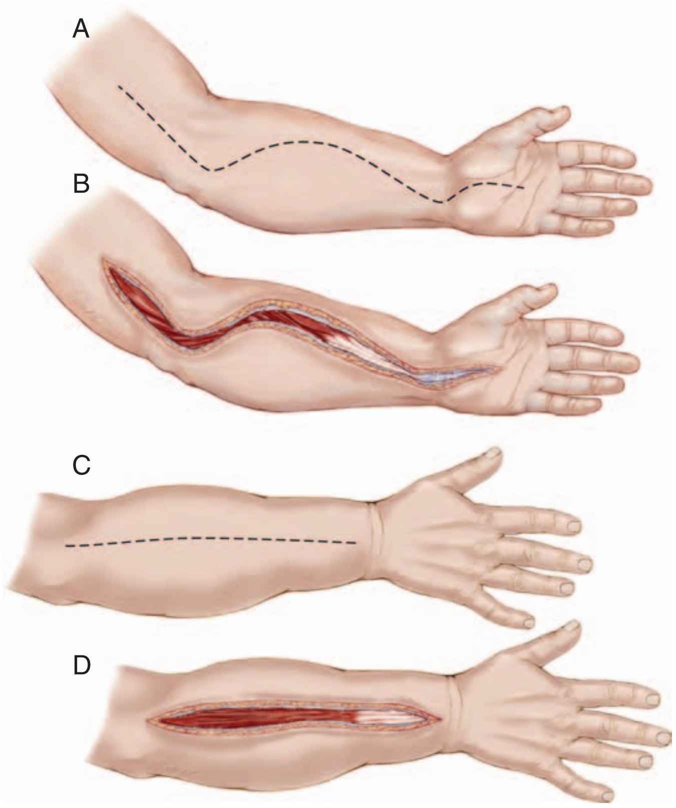
f0030

FIGURE 51.5 Cross section of the midarm with *arrows* showing the plane of dissection for decompression of the anterior and posterior compartments. Alternatively, separate anterior and posterior incisions can be used. *T-MH*, Triceps, medial head.

Release of the Compartments of the Arm. The anterior and pos- s0120
terior compartments of the arm can be decompressed through p0480
a single medial incision. This allows access to the neurovascular structures of the arm, the medial fascia of the biceps and brachialis in the anterior compartment, and the fascia of the triceps. Excision of the medial intermuscular septum will provide additional decompression of both compartments (Figure 51.5). The incision can be easily extended to the elbow crease and incorporated with the incision for decompression of the forearm. This also allows release of the lacertus fibrosus and access to the brachial artery. When there is no anticipated need to evaluate the brachial artery or to decompress the forearm compartments, fasciotomies can be performed through separate anterior and posterior midline incisions to decompress the flexor and extensor compartments, respectively.

Release of the Compartments of the Forearm. Several skin inci- s0125
sions have been described for the forearm. Because the surgical p0485
incisions are long and extensile, almost any incision can be used to decompress the forearm compartments (Figure 51.6). Because the incisions are left open, we prefer an incision that minimizes exposure of neurovascular structures and can be extended in a proximal direction into the medial arm and in a distal direction into the carpal tunnel (see Figure 51.6, *A* and *B*). Once the skin incision has been made, the antebrachial fascia is incised longitudinally from the lacertus fibrosus to the wrist flexion crease. This decompresses the superficial flexor compartment. The deep flexor compartment is most easily and safely exposed through the ulnar side of the forearm.[69] We begin at the mid to distal forearm and identify the interval between the flexor carpi ulnaris and flexor digitorum superficialis. The flexor digitorum profundus and flexor pollicis longus fascias are exposed and released through this interval (Figure 51.7). This is the most important component of this procedure because the

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051



f0035 **FIGURE 51.6** Extensile incision for decompression of the forearm: The incision can be extended proximally to decompress the arm and distally into the carpal tunnel. **A,** Line of skin incision for volar release. **B,** Volar incision opened from the midarm to the carpal tunnel. **C,** Line of the dorsal incision. **D,** Dorsal incision opened and fascia released.

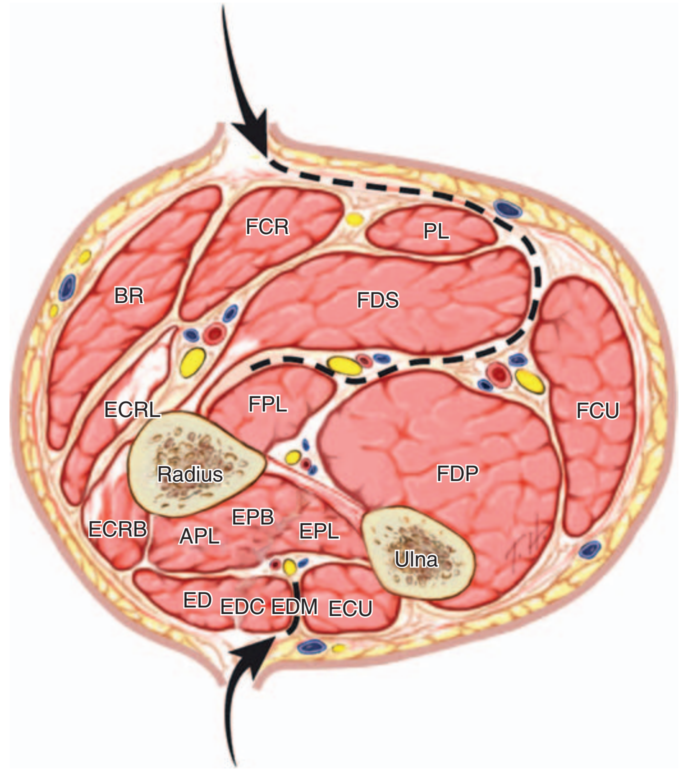


FIGURE 51.7 Cross section of the midforearm with *arrows* showing the plane of dissection for decompression of the superficial and deep flexor compartments of the volar forearm and the dorsal forearm. *APL,* Abductor pollicis longus; *BR,* brachioradialis; *ECRB,* extensor carpi radialis brevis; *ECRL,* extensor carpi radialis longus; *ECU,* extensor carpi ulnaris; *ED, EDC,* extensor digitorum communis; *EDM,* extensor digiti minimi; *EPB,* extensor pollicis brevis; *EPL,* extensor pollicis longus; *FCR,* flexor carpi radialis; *FCU,* flexor carpi ulnaris; *FDP,* flexor digitorum profundus; *FDS,* flexor digitorum superficialis; *FPL,* flexor pollicis longus; *PL,* palmaris longus. f0040

deep flexor compartment is usually the one first and most affected by increased compartmental pressure. Through the same interval, the fascia overlying the pronator quadratus is released.

p0490 During the dissection, if the muscles appear pale after release of the fascia, additional release of the epimysium of the pale muscle should be performed. For these muscles, if the epimysium is not released, reperfusion injury will lead to additional swelling within the muscle and further muscle damage.

p0495 Clinical evaluation of the remaining tension in the dorsal forearm compartment and/or hand should be done to determine whether additional release of the extensor and hand compartments should be added.

p0500 The extensor compartments are released through a midline longitudinal dorsal incision extending from the lateral epicondyle to the distal radioulnar joint. This will allow release of the mobile wad and the extensor compartment (Figure 51.8 and see Figure 51.6, *C* and *D*).

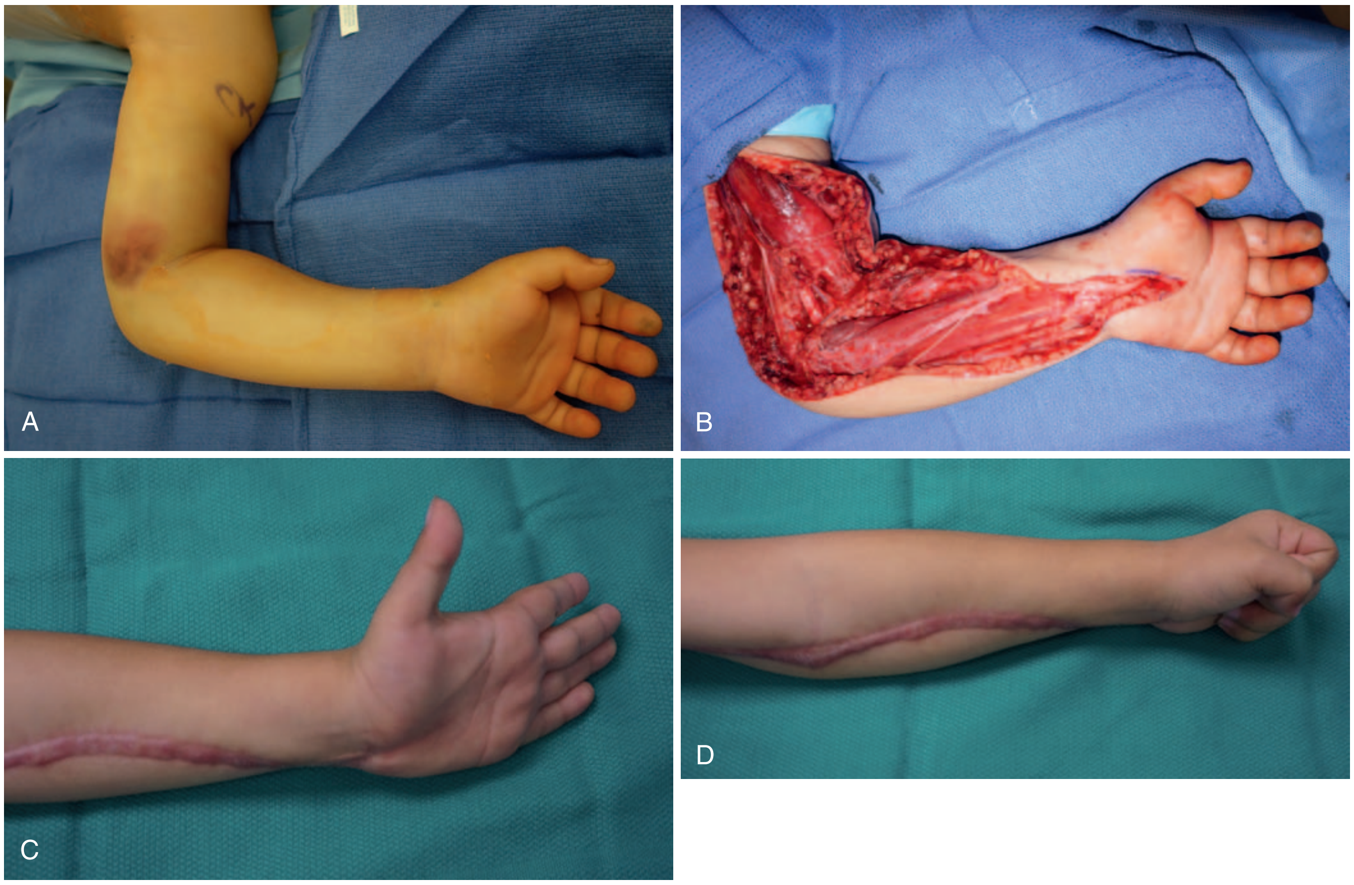
s0130 ***Release of the Compartments of the Hand.*** The hand has 10 sepa-
p0505 rate compartments. It is rarely necessary to release all 10 compartments, and intraoperative assessment and/or measurement of compartment pressures should be used to determine the extent of release needed (Figures 51.9 and 51.10).

s0135 **Volar Release.** Decompression should start with an extended
p0510 carpal tunnel release. Carpal tunnel release will usually adequately release the Guyon canal without division of the volar carpal ligament (roof of the Guyon canal) and directly decompress the ulnar neurovascular structures. The carpal tunnel incision can be extended to the second volar web space. In the distal portion of the incision, the volar fascia of the adductor pollicis muscle can be released. Also, the fascia extending from the long finger metacarpal to the palmar fascia (separating the deep radial and ulnar midpalmar spaces) can be released. This will help decompress the volar interosseous muscles. The thenar and hypothenar muscles are decompressed through separate incisions as needed.

Dorsal Release. The dorsal interosseous muscles (and volar s0140
interosseous muscles) are decompressed through dorsal inci- p0515
sions between the second and third metacarpals and fourth and fifth metacarpals. The first dorsal interosseous muscle is decompressed through an incision placed in the first dorsal web space. The dorsal fascia of the adductor pollicis can also be released through this incision (see Figure 51.9).

Release of the Fingers. Tense swollen fingers can result in skin s0145
and subcutaneous tissue necrosis. The tight fibers of Cleland p0520
and Grayson ligaments can compress and obstruct the digital arteries. Dermotomy of all involved fingers reduces the risk of necrosis of the skin and possible loss of a digit. Dermotomies should be done in the midaxial plane to prevent subsequent contracture. When possible, the dermotomy should be performed on the side that will cause the least amount of scar irritation. The preferred locations for finger and thumb dermotomies are shown in Figure 51.9, *A* and *B*.

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051



f0045 **FIGURE 51.8** This 5-year-old patient sustained a type 3 100% displaced supracondylar humerus fracture that was treated with closed reduction and pinning. Approximately 6 hours after surgery, the patient had increased pain and analgesia requirements. On examination, the compartments were tense and swollen. He was taken emergently for fasciotomy of the arm and forearm. **A,** Appearance of the arm after closed reduction and pinning after patient returned to the operating room. **B,** Fasciotomy of the arm and forearm. **C,** Final finger and wrist extension after 6 months. **D,** Final finger flexion after 6 months.

p0525 See Case Study 51.1 and Video 51.1 for further information on compartment release of the arm, forearm, and hand.

s0185 Postoperative Management

p0700 All surgical incisions are left open. We prefer not to use retention sutures. Even if there is minimal swelling of the muscle(s) during the primary release, muscle swelling will usually increase after perfusion has improved. If nerves and arteries are not exposed, a negative-pressure wound dressing (e.g., VAC, Kinetic Concepts, Inc., San Antonio, TX) can be used. We use lower pressures for the negative pressure dressing than in other wounds, usually just enough to maintain good seal on the dressing. If nerves or arteries are exposed, we prefer to use a moist gauze dressing. Dressing changes should be done in the operating room at 24 to 48 hours. Partial delayed primary wound closure can be performed at that time if swelling has decreased and/or to provide coverage over open neurovascular structures. Definitive delayed primary wound closure should be performed only after swelling has decreased. Some cases will require repeat débridement of necrotic tissue. Split-thickness skin grafting for closure is necessary in many patients. Younger patients with high-energy or crush injuries are more likely to require split-thickness skin grafting at 48 hours.[25] In our practice, we prefer to manage the wound until swelling decreases sufficiently to allow delayed primary wound closure if possible, which may require 7 to 10 days. In the hand, only the incision for the carpal tunnel release should be considered for delayed primary wound closure. The other palmar and dorsal incisions as well as the dermotomy incisions will heal quickly by secondary intention. If the skin cannot be closed without tension, split-thickness skin grafting with or without dermal substitutes such as Integra (Integra, Plainsboro, NJ) should be used.

Therapy should be started immediately following surgery to p0705 promote maximum active and passive range of motion of the fingers. Splinting should be done for soft tissue stabilization and/or for treatment of other associated injuries. Cessation of therapy during healing of skin grafts may be necessary, but therapy should be resumed as soon as tissue healing allows. Once the soft tissues are adequately healed, nighttime splinting is continued to prevent contractures of the wrist and fingers. Splinting is continued until scars and soft tissues are mature and supple.

Outcomes and Expectations s0190

Outcomes following fasciotomy depend on the duration and p0710 severity of the compartment pressure elevation and the resultant extent of muscle necrosis. Early prompt fasciotomy within the first 4 hours usually results in minimal sequelae. Delayed management results in muscle fibrosis and contracture that varies with the extent of muscle necrosis and nerve

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051

b0045 **CASE STUDY 51.1 Compartment Syndrome of the Upper Extremity**

s0405 **Surgical Approach to Treatment**

p1525 All or portions of this approach can be used, depending on the clinical setting. The approach is extensile from the arm to the distal forearm, and separate incisions are required to release the extensor compartment (when indicated). Multiple incisions are used to release the compartments of the hand.

s0410 **Fasciotomy of the Upper Extremity**

p1530 Incisions are designed to provide the most coverage of neurovascular structures (at the time of later closure). Linear incisions across flexion creases are avoided. After the skin incision, the antebrachial fascia is released, allowing assessment of the superficial flexor compartment. The interval between the flexor digitorum superficialis and flexor carpi ulnaris is opened to provide access to the deep flexor compartment of the forearm.

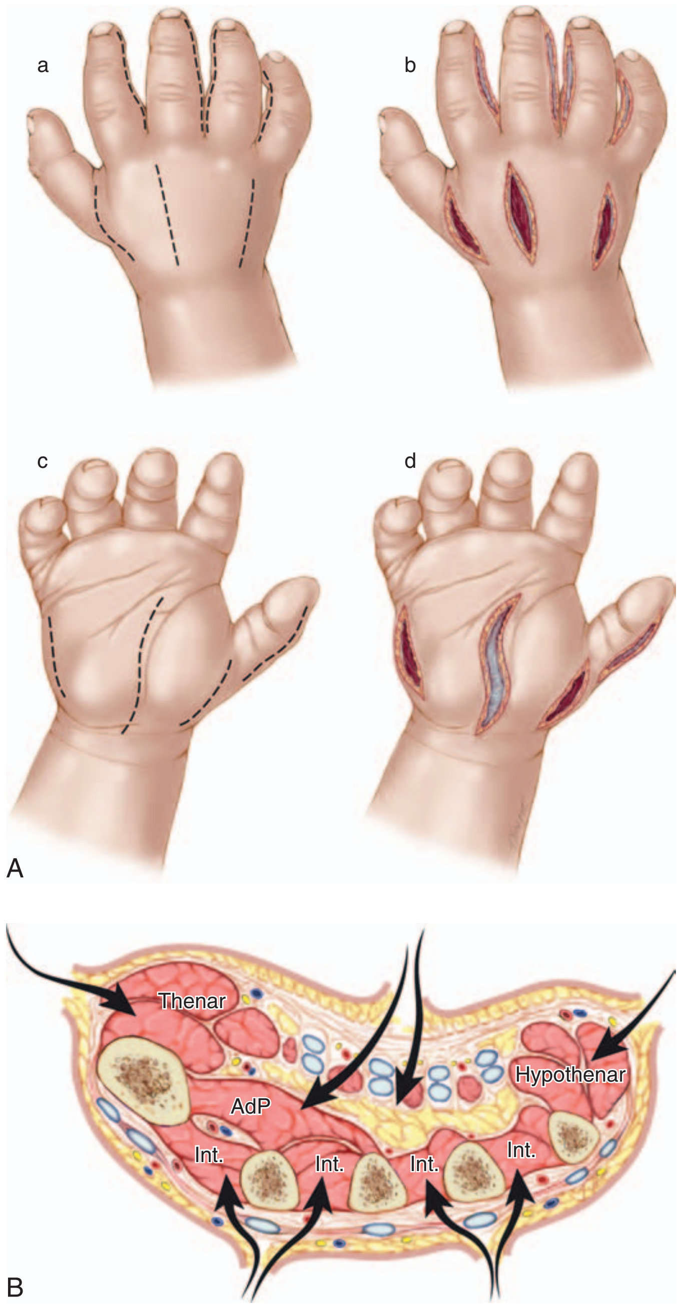
p1535 After release of the flexor compartments, muscles are inspected and epimysiotomies are performed for tense or dysvascular muscles. Once the flexor compartments are released, the extensor compartment is assessed. If tense, this is released through a dorsal midline incision.

p1540 Release at the elbow requires division of the lacertus fibrosus with exploration of the median nerve and brachial artery. Fasciotomies in the hand are performed through a carpal tunnel release, release of the thenar and hypothenar eminences, and dorsal incisions for the release of the interosseous muscles.

p1545 Decompression of the fingers may be necessary to prevent digital loss. This is performed through midlateral incisions, avoiding pinching surfaces, including the radial border of the thumb, ulnar borders of the index and long fingers, and radial borders of the ring and small fingers.

p1550 The Cleland ligaments are released when necessary to decompress the digital arteries (see Video 51.1).

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051



f0050 **FIGURE 51.9 A,** Incisions for decompression of the hand. **B,** Cross section of the midhand showing planes of dissection for surgical decompression. *AdP,* Adductor pollicis; *Int.,* interosseous muscles.

CRITICAL POINTS *Compartment Syndrome* b0020

Diagnosis s0150

- Diagnosis is usually a clinical one p0530
- Pain is out of proportion to clinical findings u0230
- Pain with passive motion u0235
- Firm, "rock hard" compartment u0240
- Objective findings include elevated compartment pressures and 30 to 40 mm Hg or within 30 mm of diastolic blood pressure or mean arterial pressure u0245

Management s0155

- Correct any underlying coagulopathy p0560
- Perform emergent fasciotomy u0255
- Perform vascular repair or reconstruction when indicated u0260
- Treat associated injuries u0265
- Repeat surgical débridement u0270
- Close the wound with delayed primary closure, split-thickness skin graft, or flap u0275
- Perform early reconstruction when indicated with tendon transfer or functional muscle transfer u0280

Arm Management s0160

- Anterior and posterior compartments p0600
- Medial incision to decompress both compartments u0290
- Deltoid may require epimysiotomy u0295

Forearm Management s0165

- Deep volar, superficial volar, and extensor compartments p0620
- Deep compartment must be released u0305
- Best decompressed through the interval between the flexor carpi ulnaris and the ulnar side of the flexor digitorum superficialis u0310
- Extensor compartment may soften with release of volar compartments but requires separate assessment and release if indicated u0315

Hand Management s0170

- Ten separate compartments p0645
- Start with extended carpal tunnel release u0325
- Release additional compartments as necessary u0330

Finger Management s0175

- Tense, swollen fingers can result in digital necrosis p0665
- Midlateral dermotomies are performed dorsal to the neurovascular bundles u0340

Pitfalls s0180

- Failure to diagnose in a timely manner p0680
- Failure to adequately release compartments u0350
- Inadequate excision of necrotic tissue leading to scarring and fibrosis around nerves u0355

involvement. Secondary surgery is usually necessary to improve the outcome of these delayed cases.

p0715 Outcomes following fasciotomy for chronic exertional compartment syndrome are good. Preoperative symptoms of pain related to activity resolve, and 90% of patients are able to return to sports or other activities.[10,31,41,88,91]

p0720 Complications of compartment syndrome and its treatment are common. In a metaanalysis, Kalyani and colleagues reported a complication rate of 42% (18 of 43 patients).[46] Duckworth and associates reported a complication rate of 32% (29 of 99 patients). The most common complication was a neurologic deficit. Other complications included contracture, reflex sympathetic dystrophy, gangrene, muscle weakness, fracture nonunion, and soft tissue tethering associated with skin grafting.[25]

VOLKMANN CONTRACTURE s0195

Volkmann ischemic contracture is the end result of prolonged ischemia and associated with irreversible tissue necrosis. Established Volkmann contracture has a much different presentation than ACS. It has a broad clinical spectrum, based on the extent of muscle necrosis and degree of nerve injury. Unlike ACS, patients with an ischemic contracture do not have pain but rather have deformity and dysfunction resulting from the p0725

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051

f0055

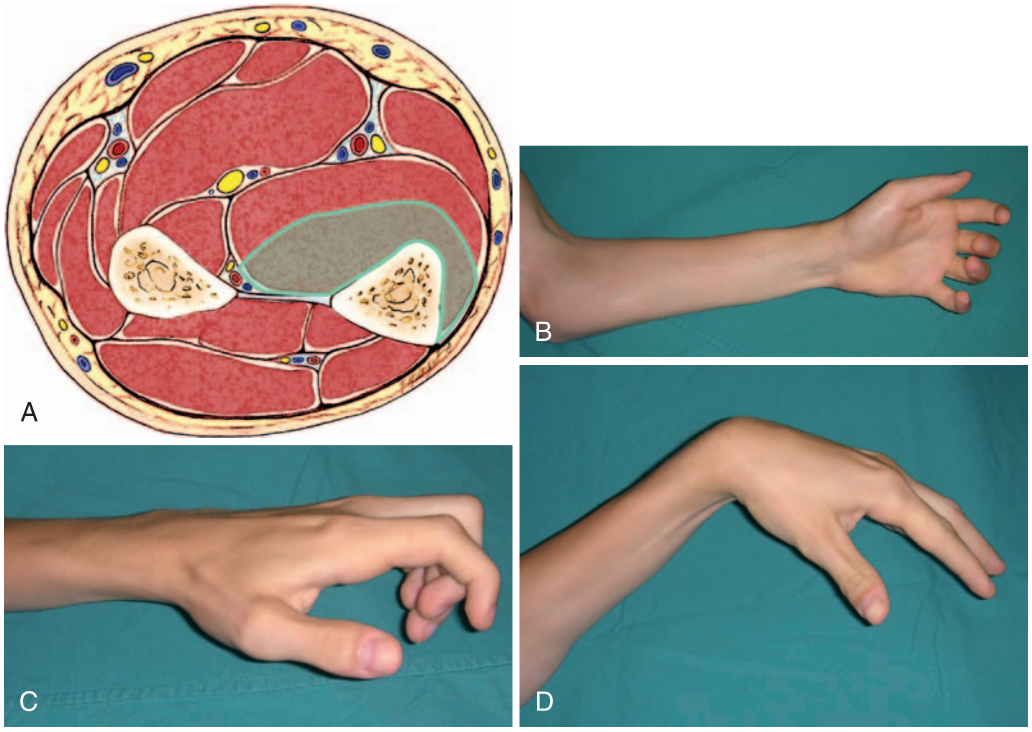
FIGURE 51.10 A 2-year-old sustained a crush injury to his left hand, with fractures of the second to fourth metacarpal bases and an open wound at the volar metacarpal heads. He presented with a tense swollen hand. He was taken emergently for fasciotomies of the hand and underwent percutaneous pinning of the displaced metacarpal base fractures. **A,** Appearance of the hand at presentation. **B,** Metacarpal base fractures, 100% displaced in the sagittal plane. **C,** Fasciotomies of the volar hand. **D,** Fasciotomies of the dorsal hand. **E,** Final extension at 9 months following injury. **F,** Final flexion at 9 months following injury.

ischemic event and subsequent muscle scarring and fibrosis. Nerve dysfunction can occur either from the initial trauma or subsequent ischemic insult or secondary to the fibrosis around the nerves. The muscle fibrosis and neurologic deficits lead to deformity of the joints distal to the site of ischemia. The deformity is progressive over the ensuing weeks to months. In children, an untreated deformity will progress until skeletal maturity because the ischemic muscles are unable to elongate during limb growth. Even when the contractures are treated, the affected extremity is shortened due to the tethering across the physis.

Classification s0200

Several classification systems have been described for Volkmann contracture of the forearm. Most are based on the extent of muscle involvement and the severity of the clinical disability. The classification systems can be useful in guiding treatment plans for functional reconstruction. Most authors recognize the p0730

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051



f0060 **FIGURE 51.11** **A,** Cross-sectional representation of a mild Volkmann contracture (according to Tsuge classification) at the midforearm level. **B,** Volar clinical appearance of mild Volkmann contracture. **C,** Lateral view appearance of mild Volkmann contracture. **D,** Mild contracture allows for full extension of the fingers when the wrist is positioned in volar flexion.

t0030 **TABLE 51.5 Tsuge Classification for Volkmann Contracture of the Forearm**

	Type	Findings	Treatment Options
u0360	Mild	Localized Volkmann contracture	Nonsurgical treatment
u0365		Usually involves principally the deep flexor compartment	Stretching
u0385		(flexor digitorum profundus of long and ring fingers	Splinting
u0390		most affected)	Must be maintained through skeletal maturity
u0370		Little or no nerve involvement	Surgical treatment
u0400			Selective fractional lengthening
u0405			Selective flexor origin slide
u0410	Moderate	Most or all of flexor digitorum profundus and flexor	Surgical treatment
u0435		pollicis longus	Flexor origin slide
u0415		Partial flexor digitorum superficialis	Fractional lengthening
u0420		Neurologic impairment present	Shortening of forearm
u0425		Sensory in median nerve more than ulnar nerve	Proximal row carpectomy
u0455	Severe	All of flexor compartment	Surgical treatment
u0460		Varying involvement of extensor compartment	Tendon transfer
u0465		Severe neurologic deficits, including sensory deficits and	Functional free muscle transfer
u0485		intrinsic dysfunction	Both may need to be performed
u0490			Both may require adjunctive flexor slide, infarct excision, and/or contracture release
u0495			Nerve reconstruction frequently necessary

tremendous variability of the clinical presentations and the subsequent limitations of the classification systems.[73,85,86,94]

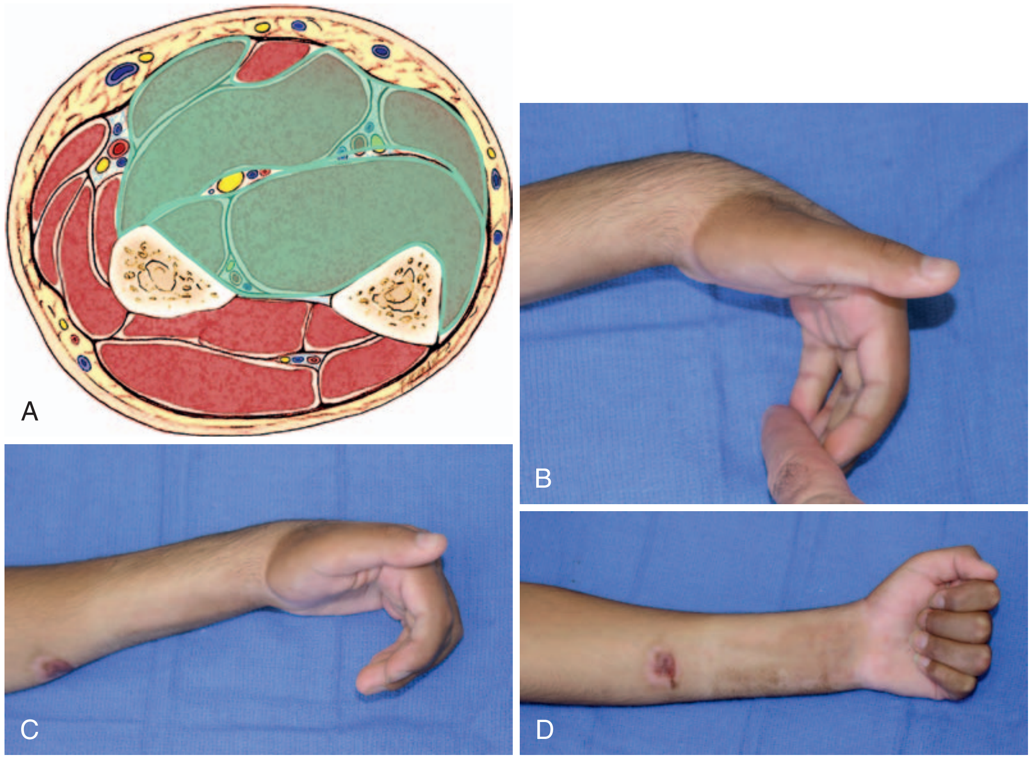
p0735 The most commonly used, and our preferred, classification system is that proposed by Tsuge.[85] Established Volkmann contracture was divided into mild, moderate, and severe types, according to the extent of muscle involvement (Figures 51.11 through 51.13 and Table 51.5). Tsuge's category of severe contractures included cases of moderate tissue necrosis that were exacerbated by fixed joint contractures, a scarred soft tissue envelope, or failed surgeries.

Within each classification type, there is a broad range of clinical presentations. The heterogeneity of presentation makes it difficult to apply a specific treatment based solely on the classification system. The variability also confounds meaningful outcome and comparison studies. p0740

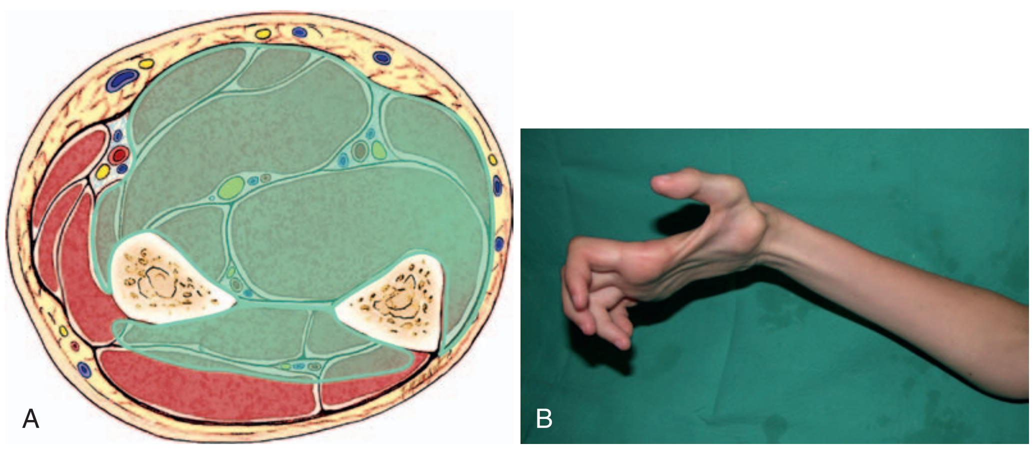
Treatment s0205

There is a limited role for the nonoperative treatment of established contracture. There may be some benefit from therapy to stretch and splint mild contractures. In children, splinting is p0745

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051



f0065 **FIGURE 51.12** **A,** Cross-sectional representation of moderate Volkmann contracture (according to Tsuge classification) at the midforearm level. **B,** Patient with Tsuge moderate Volkmann contracture. With the wrist in a position of volar flexion, the fingers cannot be brought into full passive extension. **C,** Finger flexion contracture is worsened by the wrist being brought into a neutral position. **D,** Patient demonstrates full active finger flexion.



f0070 **FIGURE 51.13** **A,** Cross-sectional representation of severe Volkmann contracture (according to Tsuge classification) at the midforearm level. **B,** Patient with severe contracture with extensive intrinsic wasting secondary to neurologic involvement at the forearm.

continued until skeletal maturity. Moderate and severe contractures are usually recalcitrant to therapy.

s0210 **Operative Treatment**

p0750 A variety of surgical techniques have been proposed, including bony and soft tissue management (Table 51.6).

s0215 p0895 ***Bone Procedures.*** Skeletal shortening or fusions are frequently performed in conjunction with some of the soft tissue procedures listed in Table 51.6. Shortening procedures include shortening osteotomy of the radius and ulna[68] and proximal row carpectomy.[34] These procedures have been used to match the skeletal length to the shortened fibrotic muscle. One concern with bone procedures is that the principal contracture is within the flexor compartment. Shortening the forearm indiscriminately lengthens the muscle resting length of both the flexor and extensor muscles, neglecting the predominant involvement of the contracture within the flexor compartment muscles. Shortening procedures raise additional concerns in children because the forearm is already shortened by the initial ischemic insult to the bone and growth plates.

Bony reconstructive procedures are useful for residual problems related to nerve dysfunction or for long-standing contractures not amenable to additional soft tissue release. Options include wrist fusion, trapeziometacarpal joint fusion, or thumb metacarpophalangeal joint fusion. Severe progressive finger deformities can also be managed with arthrodesis in a more p0900

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051

t0035 **TABLE 51.6 Surgical Options for Management of Volkmann Ischemic Contracture of the Forearm**

Late Management of Compartment Syndrome; Surgical Options for the Forearm

Operation	Authors	Advantages	Disadvantages
Bone			
Proximal row carpectomy	Zancolli, 1979[94] Goldner, 1975[34]	Addresses wrist flexion contracture without causing additional scarring in the forearm	(1) Nonselective shortening of both extensors and flexors (2) Limb is already shortened from ischemic insult
Diaphyseal shortening	Rolands, 1905[68] Domanasiewicz, 2008[24a] Pavanini, 1975[64a]	Satisfactory correction of contracture Does not preclude other procedures	(1) Nonselective shortening of both extensors and flexors (2) Limb is already shortened from ischemic insult (3) High nonunion and refracture rate reported
Arthrodesis	Botte, 1998[8] Goldner, 1975[34]	Wrist: Maintains wrist in physiologic position; if additional tendon transfers are needed, if wrist is fused, one less donor muscle is needed and wrist extensor muscles are available as donors for finger function PIP: Fingers maintained in a more functional position; may be only option to correct intrinsic imbalance	Wrist: (1) Loss of tenodesis effect of wrist position (2) Decreased grip strength (3) Loss of motion PIP: (1) Loss of finger flexion (2) Resultant loss of grip strength
Soft Tissue			
Fractional or tendon "Z"-lengthening	Goldner, 1975[34]	Straightforward surgical release of flexion contracture	(1) Loss of active flexion (2) More disruption of muscle resting length and loss of flexion strength
Infarct excision with tendon reconstruction/ transfer	Seddon, 1964,[73] Seddon, 1956[74] Tsuge, 1975[85]	Tsuge advocated infarct excision for mild contractures with involvement of only one or two fingers	(1) Late infarct excision creates more scarring around nerves (2) Deficit created from scar excision is replaced with more scar tissue later
Flexor-pronator slide	Page, 1923[64] Scaglietti, 1957[72] Gosset, 1956[34a] Sharma, 2012[75]	Allows greatest correction of flexion contracture with least impact on muscle resting length	(1) Will not fully correct finger flexion contracture that is not passively correctable in maximal wrist flexion (2) Wide surgical dissection with potential injury to CIA/PIA
Functional free muscle transfer	Zuker, 1989,[96] Zuker, 2007[98] Manktelow, 1978[55a] Manktelow, 1989[55b] Doi, 1993[24]	Only procedure that can restore function for severe contracture according to Tsuge classification	(1) Difficult microsurgical procedure requiring an experienced team (2) Failure can only be remedied with a second functional free muscle transfer

functional position. These procedures are ideally done after skeletal maturity but may need to be performed earlier if there is progressive deformity. In these cases, we attempt to fuse the joint and preserve the growth plate (i.e., chondrodesis).

s0220 ***Soft Tissue Procedures.*** p0905 Soft tissue procedures include excision of the infarcted muscle, fractional or "Z"-lengthening of the affected muscles, muscle sliding operations (flexor origin muscle slide), neurolysis, tendon transfers, and functional free-tissue transfers, as well as combinations of these procedures.[16,17,27,34,37,45,50,52,67,73,74,82,85,86,96,98] Excision of scarred fibrotic nerves without distal function followed by nerve grafting has been described to try and establish some protective sensation in the hand.[44] Fixed contractures of the joints can be addressed with soft tissue release, including capsulectomy and collateral ligament recession or excision, depending on the joints involved.

s0225 ❖ AUTHORS' PREFERRED METHODS OF TREATMENT

p0910 Our preferred methods of treatment depend on the general classification of severity of contracture, individualized to the patient presentation.

Mild (Localized) Type (Deep Flexor Compartment Without Neurologic Deficit). s0230 For mild contractures that have failed to respond p0915 to nonsurgical management, our preferred treatment is a muscle sliding operation initially described by Page and subsequently endorsed by several others.[52,61,64,72-75,85] We have found this procedure effective as long as good active finger flexion is present. We do not combine this procedure with infarct excision, nor have we found it necessary to release the distal insertion of the pronator teres to correct pronation contracture.[52,85]

A limited flexor slide may be done for mild deformity, affecting only a portion of the flexor digitorum profundus. p0920 Because the flexor digitorum profundus originates solely from the ulna, the flexor pronator mass does not have to be released from the medial epicondyle and the ulnar nerve does not have to be transposed. This limited approach reduces potential scarring and vascular compromise to the remaining muscles and nerves in the flexor compartment.

Moderate Type (Deep and Superficial Flexor Compartment With Neurologic Deficit). s0235 For moderate deformity, we prefer a flexor p0925 muscle origin slide to correct the tightness of the flexors, provided that there is still adequate remaining strength in the

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051

flexors. Because neurologic impairment is characteristic of the moderate injury, we combine the flexor slide with neurolysis of both the median and ulnar nerves. A separate incision to release the carpal tunnel may also be needed. Depending on the functional deficits, tendon transfer can be combined with flexor origin slide, either as a staged or simultaneous procedure.

s0240 p0930 ***Reconstruction of Thumb Function.*** Our preferred transfer for thumb flexion is to transfer the brachioradialis or extensor carpi radialis longus to the flexor pollicis longus. The extensor indicis proprius can be used for thumb opposition at a later date.

s0245 p0935 ***Reconstruction of Finger Flexion.*** When the finger flexors are very weak or absent, an FFMT may produce a better functional result than a tendon transfer. However, if an FFMT is not an option, tendon transfers may be considered depending on the availability of donors. The best option is transfer of the extensor carpi radialis longus to the flexor digitorum profundus because this transfer is synergistic and easy to relearn. Other lesser options include the biceps brachii elongated with graft, the brachioradialis, the extensor carpi ulnaris, and the extensor indicis proprius. Many of these secondary options do not have sufficient excursion to match the flexor muscles, but in the absence of other options, they can provide some improvement in grasp. Lastly, if there is minimal involvement of the flexor digitorum superficialis muscle, this muscle can be used as a donor to the flexor digitorum profundus

s0250 p0940 ***Nerve Reconstruction.*** When sensory impairment is severe and there has been no recovery, the nerve should be carefully evaluated at surgery. A densely scarred atrophic nerve or avascular nerve requires resection back to fascicles that appear healthy followed by sural nerve grafting to restore protective sensation to the hand (Figure 51.14).

s0255 p0945 ***Severe Type (Superficial and Deep Flexor Compartments, Extensor Compartment, and Severe Neurologic Deficits).*** Severe contractures are best treated with FFMTs.[16,18,24,45,50,92,95,96] The donor vessels are usually either the radial or anterior interosseous artery for an end-to-end anastomosis or the brachial artery for an end-to-side procedure. The donor motor nerve is the anterior interosseous nerve, which should be resected back to fascicles that appear healthy. Our preference for the donor muscle is the gracilis. For severe contractures with extensive involvement of both flexor and extensor compartments, a double free muscle transfer should be considered. Tendon transfer, nerve graft reconstruction, and late osseous reconstructive procedures may improve final functional outcomes.

s0260 ***Surgical Techniques***

s0265 p0950 **Flexor Pronator Slide.** Both volar and ulnar incisions have been described for the surgical approach for a flexor pronator slide.[64,85] We favor the incision and technique initially described by Page[64] with minor modifications (Figure 51.15). The surgical incision begins on the medial distal arm and continues along the ulnar border of the forearm all the way to the wrist. The ulnar nerve is identified and mobilized for several centimeters proximal and distal to the medial epicondyle, including proximal release at the arcade of Struthers. Approximately 4 to 6 cm of intermuscular septum between the brachialis and triceps is excised to prevent kinking of the ulnar nerve after transposition. The flexor pronator mass is elevated off of the medial epicondyle, taking care to preserve the medial collateral ligament and elbow joint capsule. Inadvertent disruption of the joint capsule is repaired. The origins of the flexor carpi ulnaris,

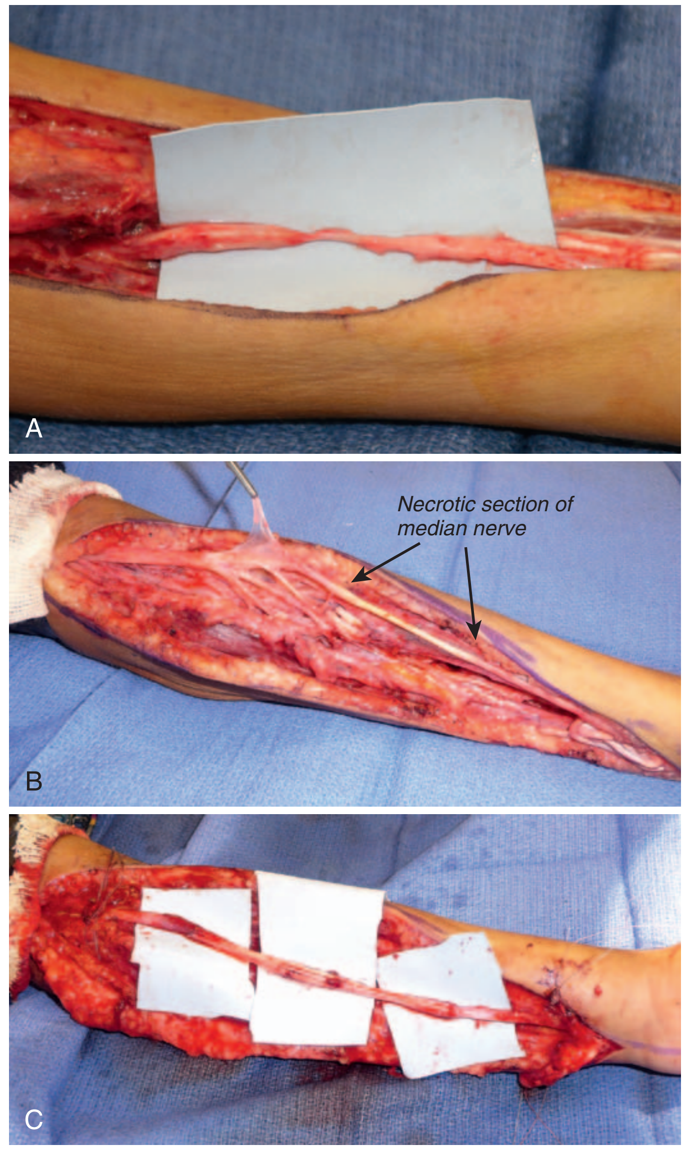
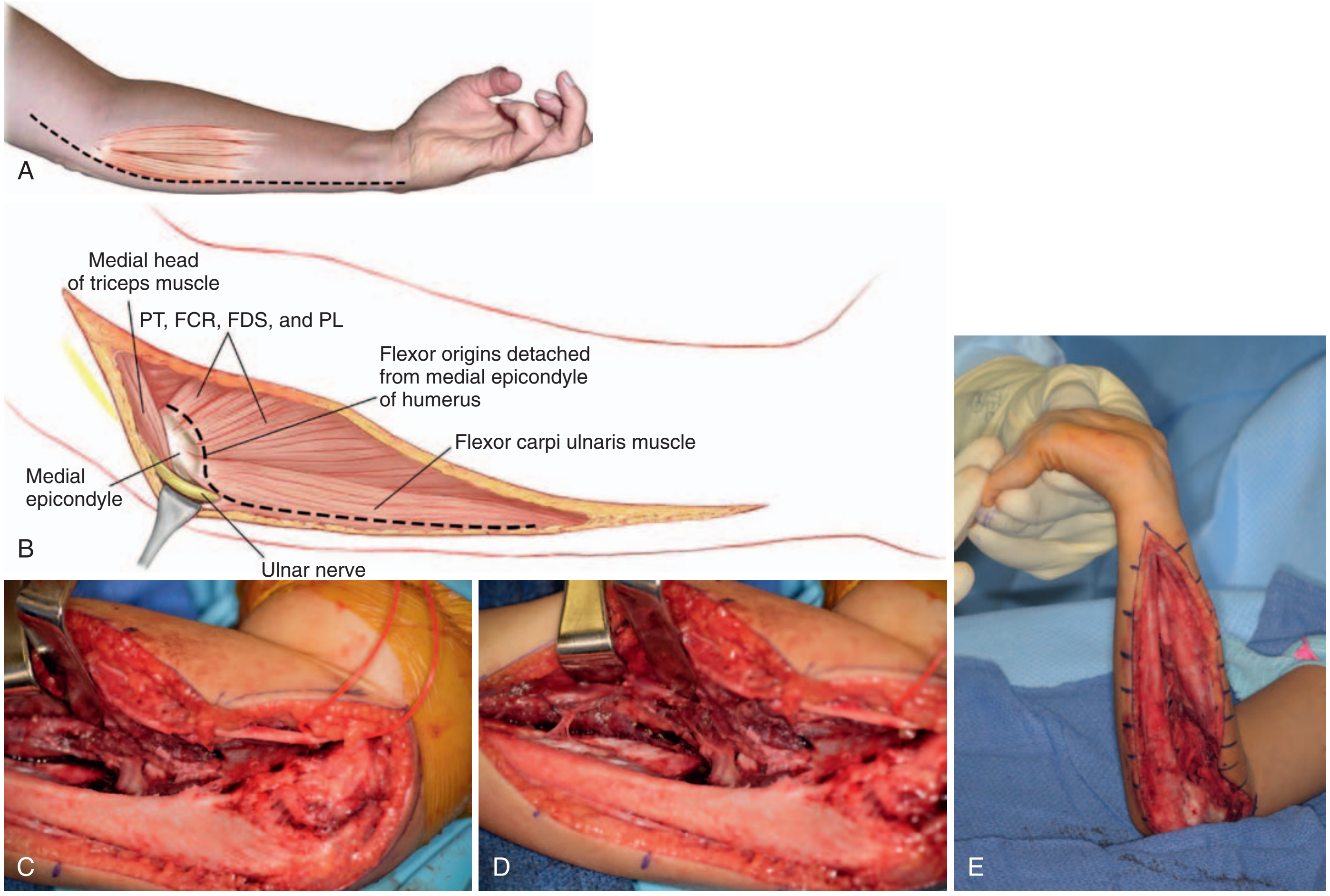


FIGURE 51.14 **A,** Scarred nerve. **B,** Avascular nerve. **C,** Reconstructed nerve. f0075

flexor digitorum profundus, and flexor digitorum superficialis are mobilized off of the ulna and interosseous membrane. The dissection is carried out above the periosteum toward the radius. The common interosseous artery arises as a branch of the ulnar artery and must be protected. This artery crosses the flexor digitorum profundus, where it bifurcates into the anterior and posterior interosseous arteries (see Figure 51.15, *C*). The posterior interosseous artery enters the posterior compartment at the proximal edge of the interosseous membrane. Because the posterior interosseous artery is the dominant blood supply to the extensor compartment, protection of this branch is mandatory.

Continuing the dissection toward the radius, the origin of p0955 the flexor pollicis longus is released from proximal to distal. Special attention is needed in this area to protect the anterior interosseous nerve. Throughout the procedure, the wrist and fingers are manipulated to check whether the contracture is improving and to help determine whether there are still areas of tightness within the muscle origin. The dissection must

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051



f0080

FIGURE 51.15 **A,** Diagram of surgical incision for flexor origin slide. **B,** Schematic diagram of deeper layer of dissection for flexor origin slide. **C,** Ulnar incision with ulnar nerve identified and mobilized. Flexor pronator mass elevated from the medial epicondyle with preservation of the medial collateral ligament and elbow joint capsule. **D,** Dissection proceeds in a radial direction with protection of the interosseous arteries. **E,** Complete release heralded by full finger wrist extension with the wrist held in extension. *FCR*, Flexor carpi radialis; *FDS*, flexor digitorum superficialis; *PL*, palmaris longus; *PT*, pronator teres.

often be carried down to the level of the wrist to release adhesions between the flexor tendons and pronator quadratus before full correction is achieved. If necessary, the carpal tunnel should be opened and tendon adhesions released in this area. It has been our experience that the lacertus fibrosus and superficial fascia around the antecubital fossa are often tight and are contributing to the residual elbow flexion contracture. The fascia can also tether the superficial flexors of the wrist and fingers, contributing to incomplete correction of the wrist and fingers with the muscle sliding only. Release of this fascia helps correct the deformity and also prevents median nerve compression between the heads of the pronator teres. Slight undercorrection, which can be addressed by postoperative splinting and rehabilitation, may decrease the reduction in muscle power resulting from the muscle slide. When a pronation contracture is present and has not been corrected by the release of the flexor-pronator origin, we release the pronator quadratus from the distal ulna. Even with a complete release of both the pronators and the volar distal radioulnar joint capsule, complete correction of the pronation deformity may not be possible due to fibrosis and contracture of the interosseous membrane. At the completion of the muscle slide, the ulnar nerve is transposed to an anterior subcutaneous position. The hand is casted in a position of forearm supination with the wrist and fingers in full extension. Immobilization is continued for a period of 6 weeks to allow the flexor pronator to heal adequately to its new origin (Figure 51.16) and Case Study 51.2.

Restoration of Extrinsic Flexor Function. s0285
For moderate contractures, a muscle slide may leave adequate flexor muscle p1060
function. Commonly, flexor strength and excursion are weakened and can benefit from flexor reconstruction. The options for tendon transfer depend on the extent of muscle necrosis in the forearm. Donor muscles from the extensor compartment can be used to reconstruct finger flexion and thumb flexion and opposition. Our preferred transfers are transfer of the extensor carpi radialis longus through the interosseous membrane to the flexor digitorum profundus, transfer of the brachioradialis to the flexor pollicis longus, and transfer of the extensor indicis proprius to restore opposition of the thumb.

Secondary options may be available in the flexor compart- p1065
ment when there is involvement of the deep flexor compartment only. A transfer of the flexor digitorum superficialis to the

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051

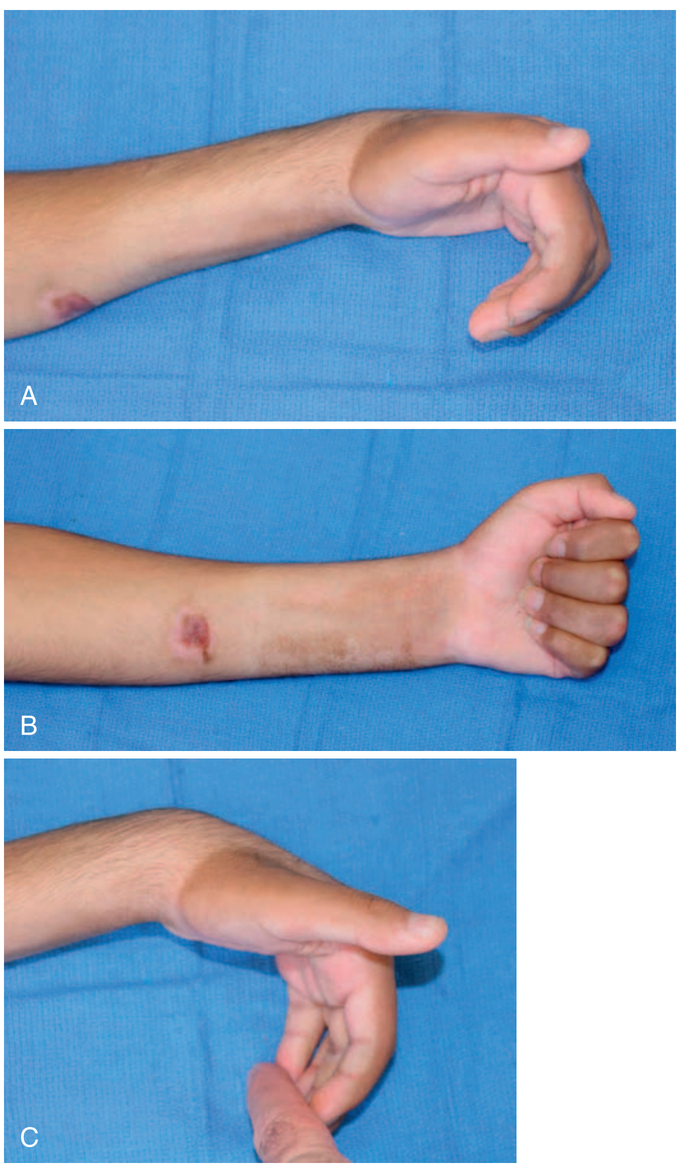
b0050 **CASE STUDY 51.2 Moderate Volkmann Contracture**

p1555 A 15-year-old right hand dominant football player sustained a minimally displaced but angulated left both-bone forearm fracture. The fracture was treated in a long-arm cast with extreme molding at the midforearm. When the cast was removed at 6 weeks, the patient was noted to have a flexion contracture of the thumb and fingers. The fingers could be extended only with maximum wrist flexion. He could actively flex his fingers into a full fist. The patient was seen in the hand surgery department at 9 months after injury (eFigure 51.1).

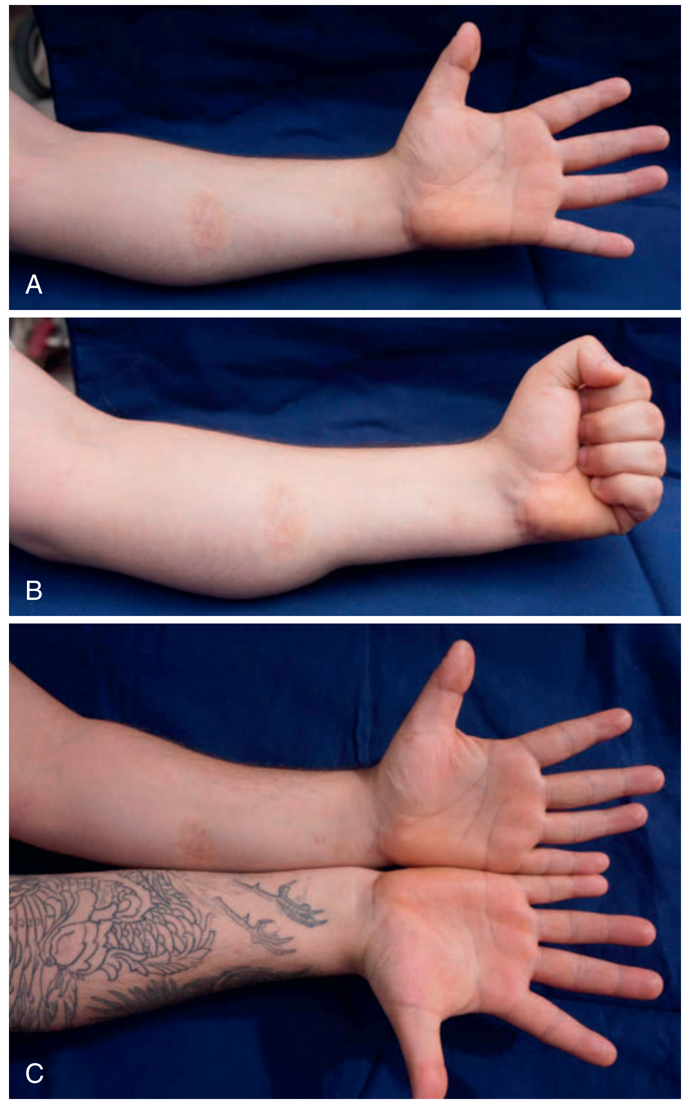
p1565 At 9 months following injury, the patient underwent a flexor origin slide. A cast was applied with the wrist, fingers, and thumb in maximum extension for 6 weeks after surgery. At the time of cast removal, the patient was seen in therapy. A nighttime extension splint was made and recommended for use for 1 year after surgery. (The patient reported that he used this splint only for a few weeks.)

p1570 At 10 years of follow-up, the patient is working in light construction and builds motorcycles.

p1575 He feels happy with the outcome and grip strength, although he reports occasional fatigue in the forearm with prolonged use (eFigure 51.2 and Video 51.2).



f0110 **eFIGURE 51.1** Moderate Volkmann contracture. **A** and **B,** Presentation at 9 months following injury. **C,** Intraoperative passive extension.



f0115 **eFIGURE 51.2** Ten-year follow-up after flexor origin slide. **A,** Full finger extension with wrist in full extension; slight thumb interphalangeal flexion. **B,** Full thumb and finger flexion with grip strength 85% of contralateral side. **C,** Mild shortening of the affected forearm.

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051

b0025 **CRITICAL POINTS *Flexor Pronator Slide for Volkmann Contracture***

s0270 **Preoperative Planning**

p0960 • Indications include mild and moderate contractures of the forearm muscles
u0505 • Special evaluations include clinical examination of flexor muscle strength and preoperative magnetic resonance angiogram or arteriogram when indicated for previous vascular injury or by an abnormal vascular examination
u0510 • Bipolar cautery is useful for this procedure

s0275 **Surgical Technique**

p0980 • Incision from ulnar side from middle third to distal third junction of the arm, following the course of the ulnar nerve and continuing along the border of the forearm to the wrist flexion crease (extensile ulnar approach)
u0520 • Mobilize and transpose the ulnar nerve
u0525 • Release the flexor-pronator origin off of the medial epicondyle, preserving the medial collateral ligament and joint capsule
u0530 • Release the origins of the flexor carpi ulnaris, flexor digitorum profundus, flexor digitorum superficialis, and flexor pollicis longus from the ulna and intermuscular septum, working from proximal to distal and ulnar to radial
u0535 • Identify and protect the common interosseous artery and its division into the anterior and posterior interosseous arteries
u0540 • Frequently passively extend the wrist and fingers to identify structures that remain tight; the release is complete when full passive wrist and finger extension is achieved
u0545 • A separate release of the carpal tunnel and release of tendon adhesions in this area may be necessary if complete slide fails to achieve full extension
u0550 • Residual pronation contracture is addressed by release of the pronator quadratus from its ulnar origin and release of the volar dorsal radioulnar joint capsule; complete correction may not be possible due to interosseous membrane tightness
u0555 • A large drain is placed below the flexor pronator mass (it is removed on the first postoperative day)
u0560 • No fascial closure; skin and subcutaneous tissue only are closed

s0280 **Postoperative Care**

p1035 • Immobilization in long-arm cast with the elbow at 90 degrees and the forearm in supination; the wrist and fingers are in full extension, and the thumb is in abduction and extension; the initial cast should be bivalved if swelling is a concern
u0570 • Duration of immobilization is 2 to 3 weeks in a long-arm cast; convert to short-arm cast with wrist and finger extension and thumb abduction-extension for an additional 3 to 4 weeks (full 6 weeks postoperatively)
u0575 • Rehabilitation: Begin elbow motion and nerve gliding at time of conversion from long-arm cast to short-arm cast; begin wrist and finger range-of-motion exercises with therapy guidance at time of cast removal; strengthening may begin as tolerated starting at 6 weeks; custom thermoplast orthosis at night until skeletal maturity
u0580 • Activities: The patient may return to sports when adequate strength and motion allow participation in the sport of choice; we encourage swimming activities to develop strength and motion

flexor digitorum profundus will provide the patient with good flexor strength and sufficient excursion to achieve functional grasp. Also, the flexor carpi radialis and flexor carpi ulnaris may be spared and available as donor muscles for transfers. Neither of these muscles has excursion matching that of the flexor digitorum muscles.

p1070 When the extensor compartment has been compromised by the ischemic event, the muscles are not available for transfer. For these patients, the only option for functional reconstruction remains an FFMT.

CRITICAL POINTS *Tendon Transfer for Finger and Thumb Flexion* b0030

Preoperative Planning s0290

• Careful preoperative clinical assessment of available donor muscle strength p1075

Surgical Technique s0295

• Extensor carpi radialis longus to flexor digitorum profundus, brachioradialis to flexor pollicis longus, or extensor indicis proprius to radial side of the thumb metacarpal p1085
• The extensor carpi radialis longus is harvested from the radial base of the index metacarpal through a longitudinal incision. u0595
• The harvest incision of the extensor carpi radialis longus is extended or a separate proximal incision is made at the junction of the middle third and distal third of the forearm to create a tunnel through the interosseous membrane. u0600
• The brachioradialis is exposed through the same incision used to expose the extensor carpi radialis longus proximally. The brachioradialis must be freed from the forearm fascial attachments to improve excursion. u0605
• The extensor indicis proprius is exposed through a separate incision at the metacarpophalangeal and mobilized proximally. u0610
• A volar incision is made at the distal third of the volar forearm to identify and mobilize the flexor digitorum profundus tendons. The flexor pollicis longus is identified through the same incision. The flexor digitorum superficialis tendons are excised. The flexor digitorum profundus tendons are sutured together as a single tendon unit. u0615
• The extensor carpi radialis longus is transferred through the interosseous membrane; the opening created in the interosseous membrane must be sufficient in size to prevent constriction of the transferred muscle-tendon unit. u0620
• The extensor carpi radialis longus is woven into the flexor digitorum profundus tendons using a weave technique. u0625
• The tenorrhaphy is placed under sufficient tension to restore the resting cascade of the fingers but still allow full passive extension of the fingers with the wrist in neutral position. u0630
• The brachioradialis to flexor pollicis longus transfer is completed in a similar manner. u0635
• The extensor indicis proprius is mobilized proximally, then passed through a subcutaneous tunnel around the ulnar side of the wrist. An ulnar-sided incision around the level of the pisiform is made to retrieve the extensor indicis proprius and to create a subcutaneous tunnel from the ulnar wrist to the radial side of the thumb metacarpal neck. u0640
• The extensor indicis proprius is secured to the radial side of the thumb metacarpal neck with the thumb in a position of abduction and pronation, as described by Burkhalter.[12] u0645

Postoperative Care s0300

• Immobilization is in a splint or cast: Dorsal block with wrist at 30 degrees of flexion, metacarpophalangeals at 70+ degrees of flexion, thumb in abduction and pronation with interphalangeal joint in neutral p1150
• The duration of immobilization is 4 weeks, during which time the patient is instructed in passive range-of-motion exercises u0655
• At 4 weeks, a thermoplast splint may be worn full time and place-and-hold exercises may begin. u0660
• At 6 weeks, the transition is made to nighttime use of the splint only. u0665
• Rehabilitation with place-and-hold exercises beginning at 4 weeks; passive extension after 6 weeks u0670
• Activities: The patient may return to sports when there is adequate strength and motion to participate in the sport of choice; minimum of 6 months after tendon transfer u0675

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051

f0085

FIGURE 51.16 This 42-year-old woman sustained an isolated brachial artery laceration and had a dysvascular forearm and hand. She underwent repair of the artery. She presented 1 year after injury with inability to straighten her fingers with the wrist in a neutral position (Holden type 1 contracture). **A,** Finger extension with the wrist in neutral. Flexor pollicis longus is spared. **B,** Finger extension with the wrist in neutral. **C,** Finger flexion. **D,** Flexor origin slide with release of flexor pronator mass and flexor digitorum profundus. The ulnar nerve is transposed anteriorly. The wrist and fingers are extended throughout the procedure until full extension of the fingers is achieved with the wrist in full extension. **E,** Finger flexion at 6 months. **F,** Finger and wrist extension at 6 months.

s0305 p1185 **Restoration of Extrinsic Flexor Function: Free Functional Muscle Transfer.** Functional reconstruction following Volkmann ischemic contracture was the first clinical application of FFMT. Several different donor muscles have been used to restore finger flexion, including the pectoralis major (lateral portion), medial gastrocnemius, latissimus dorsi, and gracilis. When using the latissimus dorsi muscle, we place the caudad portion of the muscle as the origin on the medial epicondyle and use the tendinous portion to attach to the profundus tendons. The gracilis (and also latissimus) has independent neuromuscular territories that can be separated and used to restore independent thumb and finger flexion. If the latissimus dorsi is being used for functional reconstruction and independent neuromuscular territories are needed, the latissimus cannot be reversed. The tendinous insertion of the latissimus dorsi should become the neoorigin of the forearm flexors, and the muscle should be separated distally to reconstruct finger and thumb flexion independently.

Our preferred muscle for reconstruction is the gracilis, due to its size match, excursion, and power. Specific points related to FFMT in the setting of Volkmann ischemic contracture are highlighted here. p1190

Prior to FFMT, procedues may be necessary to prepare the recipient site. Excision of the infarcted muscle is not necessary p1195

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051

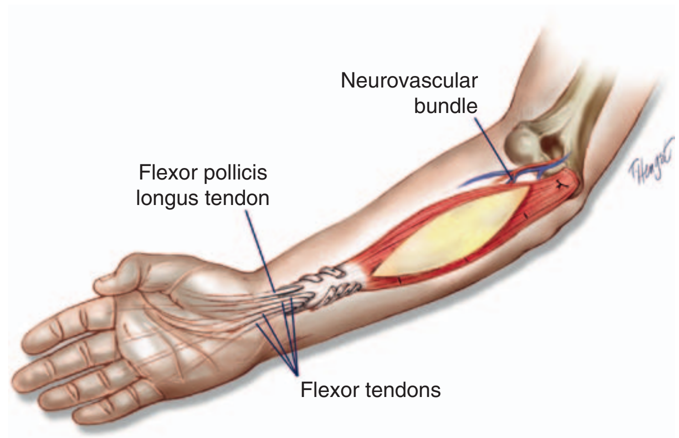
because the tendons are released distal to the area of muscle infarct. However, fixed contractures and tendon adhesions distal to the planned tenorraphy site need to be addressed.

p1200 The median and ulnar nerves (if clinically impaired) are explored. Areas of necrotic or constricted nerve are excised and grafted using a sural nerve graft. If both the median and ulnar nerves are affected over a long distance and there is not enough sural nerve graft, the median nerve should have priority of reconstruction using autogenous graft. Ulnar nerve reconstruction can be performed or augmented with nerve allograft if necessary. We prioritize median nerve function because of the importance of radial-sided sensation for pinch as well as the higher likelihood of recovery in both sensory and motor function.[14,47,48,60] In our experience, the median nerve is more frequently and more severely affected, likely due to its anatomic location.

p1205 At the time of FFMT, surgical incisions are planned to provide the best soft tissue coverage over the transferred muscle and tenorraphy site. The recipient site should be prepared *before* the donor muscle is harvested. A two-team approach is frequently used, but division of the donor tendon insertion should not be completed until the recipient vessels and motor nerve are identified. This is particularly important when using an FFMT for reconstruction in patients with Volkmann contracture. In these cases, it is often necessary to obtain intraoperative frozen sections to identify healthy fascicles of the recipient motor nerve. In addition, the vascular anastomosis should be performed proximal to the ischemic tissue bed. Even though an adequate arterial inflow may be found within the reconstruction site, the venous outflow is unreliable. The vascular pedicle and recipient nerve should be mobilized as much as possible to obtain sufficient length for proper positioning of the transplanted muscle.

p1210 The vascular anastomosis is completed first, and the muscle is allowed to perfuse for 10 to 15 minutes until the venous outflow does not appear overly dark. The anastomosis is completed as quickly as possible to minimize permanent ischemic changes to the muscle. Irreversible muscle loss increases with time in a nonlinear relationship.[5] It is our experience that if the muscle ischemia time exceeds 2 hours, the muscle will likely survive but the function will never be good. If the cause of the prolonged ischemia time can be identified (ususally, compromised venous outflow leading to reperfusion problems) and rectified (e.g., vein grafting to different recipient vessels), the surgeon can consider harvesting a different donor muscle at the same procedure.

p1215 The muscle is secured to its new origin site on the medial epicondyle using nonabsorbable suture. The origin may be secured to the periosteum and surrounding fascia. Bone tunnels or suture anchors can also be used. The muscle neoorigin should be spread out as much as possible. The tendons of the flexor digitorum superficialis are excised from the musculotendinous junction to the wrist flexion crease. The wrist and fingers are flexed so that after transection, the cut ends of the flexor digitorum superficialis will be distal to the carpal canal. The flexor digitorum profundus is divided just distal to the musculotendinous junction. The tendons are sutured side to side, with tensioning of the position to re-create the normal cascade of the fingers (Figure 51.17). When traction is applied to the sutured tendons, the fingers should all touch the midpalmar crease. The flexor pollicis longus tendon is transected distal to its musculotendinous junction. Traction is applied along the tendon to ensure proper tendon gliding. Flexor pollicis longus function is reconstucted separately using a tendon transfer if available (either the brachioradialis or extensor carpi radialis longus). If these muscles are not functional, independent flexor pollicis longus function can be restored by using the separate neuromuscular territories of the gracilis muscle to allow independent finger and thumb flexion. The transferred muscle is stretched to restore its resting length, and the site for the distal tenorraphy is marked with the wrist and fingers in full extension. The neurorraphy is completed last; its site is placed as close as possible to the transplanted muscle. Wound closure should be performed with attention to avoiding compression of the vascular pedicles. Tight skin closures should be avoided at all costs because a compartment-like syndrome or venous outflow obstruction can occur when the reperfused muscle swells following the surgery.



f0090
FIGURE 51.17 Schematic drawing of gracilis muscle used for free functional muscle transfer for reconstruction of finger flexion.

Transfer of Gracilis Muscle. The gracilis muscle is usually s0310
harvested with the patient supine in a frogleg position. Either p1220
the ipsilateral or contralateral gracilis can be used for finger flexor reconstruction because the recipient vascular pedicle and obturator nerve have sufficient length to accommodate the distance to the recipient site. Technique highlights are listed in the critical points box.

Outcomes s0345

Outcomes following Volkmann contracture in the upper p1385
extremity are difficult to assess. Studies are limited by the small numbers of patients, the great variability in the initial presentations, the varied surgical techniques used, and the difficulty in tracking patients over the long term as they grow to skeletal maturity. Ultee and Hovius attempted to provide some information regarding outcomes.[87] They found that all patients who had developed the contracture during childhood had a relatively shortened extremity. Substantial improvements in hand function were noted in patients who underwent FFMT. Tendon lengthening alone often resulted in recurrence of contracture. Finally, in patients who had sufficient remaining muscle, procedures that combined infarct excision, tenolysis, neurolysis, and tendon transfer produced good hand function.[87] Sundararaj and Mani noted improvement in sensory function in conjunction with neurolysis.[82]

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051

b0035 **CRITICAL POINTS *Free Functional Muscle Transfer for Finger Flexion***

s0315 **Preoperative Planning**

p1225 • Indications are no active finger flexion and no available tendon transfers
u0685 • Microsurgical instrumentation and magnification are required

s0320 **Surgical Technique**

s0325 ***Preparation of the Donor Site***

p1240 • Extensile surgical incision along the forearm
u0695 • Excision of necrotic and/or fibrotic muscle may not be necessary after division of the flexor tendons
u0700 • Neurolysis of the median and ulnar nerves
u0705 • Nerve reconstruction when indicated using sural nerve autograft
u0710 • Identification and preparation of the recipient nerve: recipient nerve options are the anterior interosseous nerve and the median nerve; recipient artery and vein options are the anterior interosseous artery (end-to-end), radial artery (end-to-end), ulnar artery (end-to-end), and brachial artery (end-to-side)

s0330 ***Harvest of the Gracilis***

p1270 • Frog position of the leg; a sandbag can be used to help positioning
u0720 • Mark the axis of dissection of the gracilis from the pubic tubercle to the tendon insertion of the pes anserinus
u0725 • A distal incision is made and the tendon of the gracilis is identified between the sartorius and the semitendinosus
u0730 • Tension applied to the distal tendon will help identify the axis of the muscle
u0735 • A skin paddle is incorporated into the surgical incision
u0740 • Dissection is carried down to the fascia; the gracilis is harvested within its fascial sheath (Figure 51.18); a wide harvest of fascia is taken anterior to the gracilis
u0745 • The resting length of the gracilis is marked with the hip in full abduction and the knee in full extension; marking sutures are placed at 5-cm intervals
u0750 • Dissection is best completed from distal to proximal and from posterior to anterior
u0755 • The tendon is released distally
u0760 • The muscle origin is divided after the neurovascular pedicle is mobilized and isolated
• The dominant vascular pedicle enters the muscle proximally on the anterior deep surface; the vascular pedicle arises from the profunda femoral artery; the obturator nerve enters the muscle proximal to the dominant pedicle; the nerve is stimulated to ensure that it produces a muscle contraction u0765
• The nerve is divided and the vascular pedicle is ligated *only* after the recipient site is ready u0770

Muscle Transfer s0335

• Arterial and venous anastomosis first; allow muscle to perfuse for 10 minutes p1335
• Establish and secure new muscle origin at the medial epicondyle; reset the muscle resting length; the resting length is reset with the wrist and fingers in full extension u0780
• Use a weave to secure the gracilis tendon to the flexor digitorum profundus and flexor pollicis longus; although the resting length is set with the wrist and fingers in extension, once that has been established, the repair is performed with the wrist and fingers in flexion to minimize tension at the repair site; flexor pollicis longus function is reconstructed with a tendon transfer (extensor carpi radialis longus or brachioradialis); alternatively, the separate neuromuscular territory of the gracilis can be used to create separate functional reconstruction for thumb flexion; this requires two motor donor nerves u0785
• Neurorraphy is completed last; the neurorraphy is completed close to the transplanted muscle u0790

Postoperative Care s0340

• Immobilization is with a long-arm splint followed by a long-arm cast, with the elbow at 90 degrees of flexion, wrist at 30 degrees of flexion, and metacarpophalangeals at 90 degrees of flexion; the thumb is in palmar abduction and interphalangeal flexion p1360
• Duration of immobilization is 4 to 6 weeks u0800
• Rehabilitation: After cast removal, gentle passive range of motion; more firm passive motion may start at 3 months; muscle stimulation may also start at 3 months; light and progressive strengthening after onset of muscle reinnervation u0805
• Activities: The patient should not participate in sports until at least 1 year after reinnervation, and then only when he or she has adequate strength and motion to participate in sport of choice u0810

s0350 p1390 ***Outcomes of Flexor Origin Slide.*** Since the original description of this procedure by Page in 1923, there have been few reports about it.[27,72,75,85] The most detailed report of outcomes for this procedure was published by Sharma and colleagues, who reported on patients with moderate Volkmann contracture with no fixed joint contractures, noting improvements in dexterity, sensibility, ability to flex and extend the fingers, and grip strength. In 15 of 19 patients, dexterity scores were in the good range. In 14 of 19, grip strength was in the good range and reached 20 to 87% of that of the contralateral hand (average, 75%). The authors attribute their good outcomes to careful patient selection and emphasis on postoperative therapy.[75]

p1395 In our experience, substantial functional improvement of mild and moderate contractures can result following flexor muscle slide and nerve reconstruction when indicated. Normal function is not anticipated, but a hand with protective sensation and functional grasp can often be achieved.

p1400 A flexor origin slide for severe contractures can improve passive finger and wrist motion and is useful as a first stage of treatment before functional reconstruction with tendon transfer or FFMT (Figure 51.19 and Case Study 51.3). All of these procedures have better outcomes in patients with preserved hand intrinsic function.

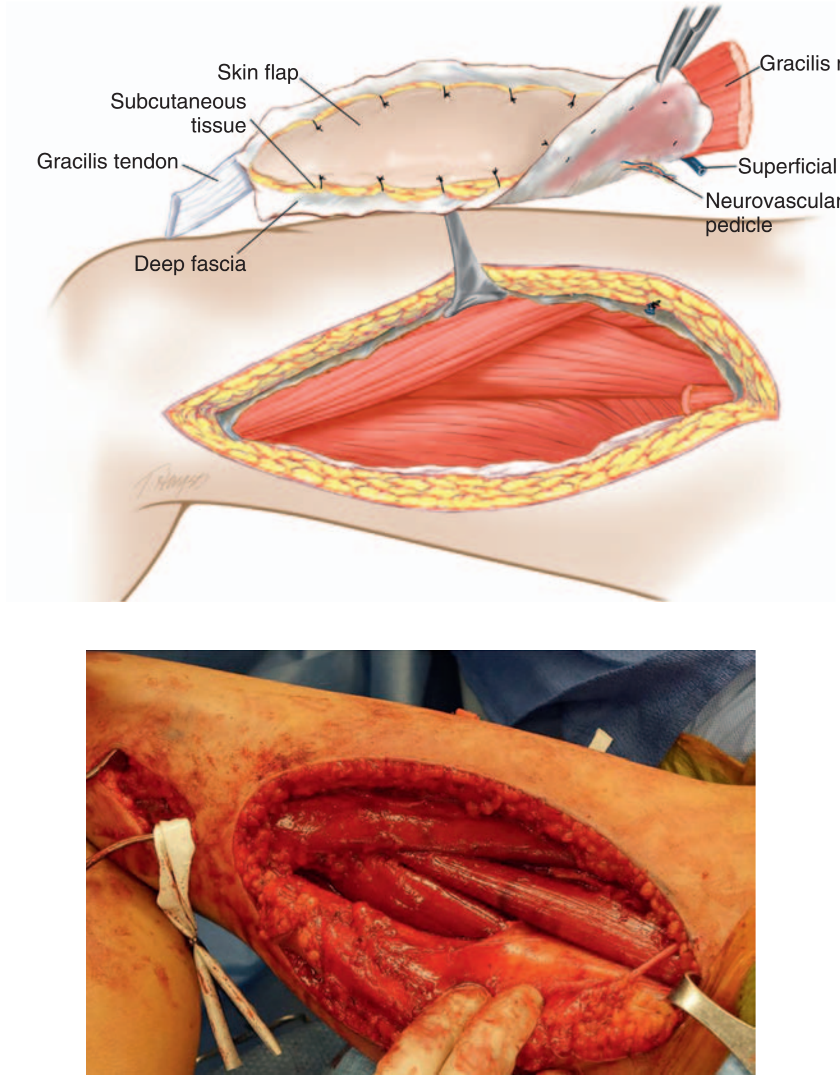
Outcomes of Free Functional Muscle Transfer. Since the first case s0355
report of an FFMT for reconstruction of finger flexion, several p1405
other case reports and small series have been reported. Zuker and colleagues reported on a series of FFMTs performed in 1991 for seven patients using a gracilis donor muscle. All patients achieved less than 2 cm of pulp to palm grip. Grip strength was approximately 25% of the contralateral side. All patients achieved a functional nondominant hand.[97] In 2011, they reported on a modification in their technique to provide independent thumb flexion by separating the fascicles of the obturator nerve and using two donor nerves, providing separate innervation to the neuromuscular territories of the gracilis muscle.[97] Krimmer and associates used the gracilis muscle in 15 patients with the primary indication being Volkmann contracture. Reinnervation occurred in 13 of 15 muscles. Ten patients achieved full active motion.[50] Liu and coworkers used the medial gastrocnemius muscle in 20 patients, reporting electromyographic activity at 6 to 20 months. Functional outcomes were reported as satisfactory, but the clinical pictures suggest

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051

b0055 **CASE STUDY 51.3 Severe Volkmann Contracture**

p1585 A 5-year-old boy developed a severe Volkmann contracture after a supracondylar humerus fracture. One year later the patient underwent a flexor origin slide to reduce the contracture at the wrist and fingers. At 2 years following injury, he underwent a free functional muscle transfer to restore finger and thumb flexion. Nerve grafting of the median nerve was performed at the same time (see Figure 51.19 and Video 51.3).

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051



f0095 **FIGURE 51.18** Dissection of gracilis.

incomplete finger flexion, likely related to the short excursion of the muscle.[55]

s0360 ***Restoration of Intrinsic Function After Volkmann Contracture of the Forearm***

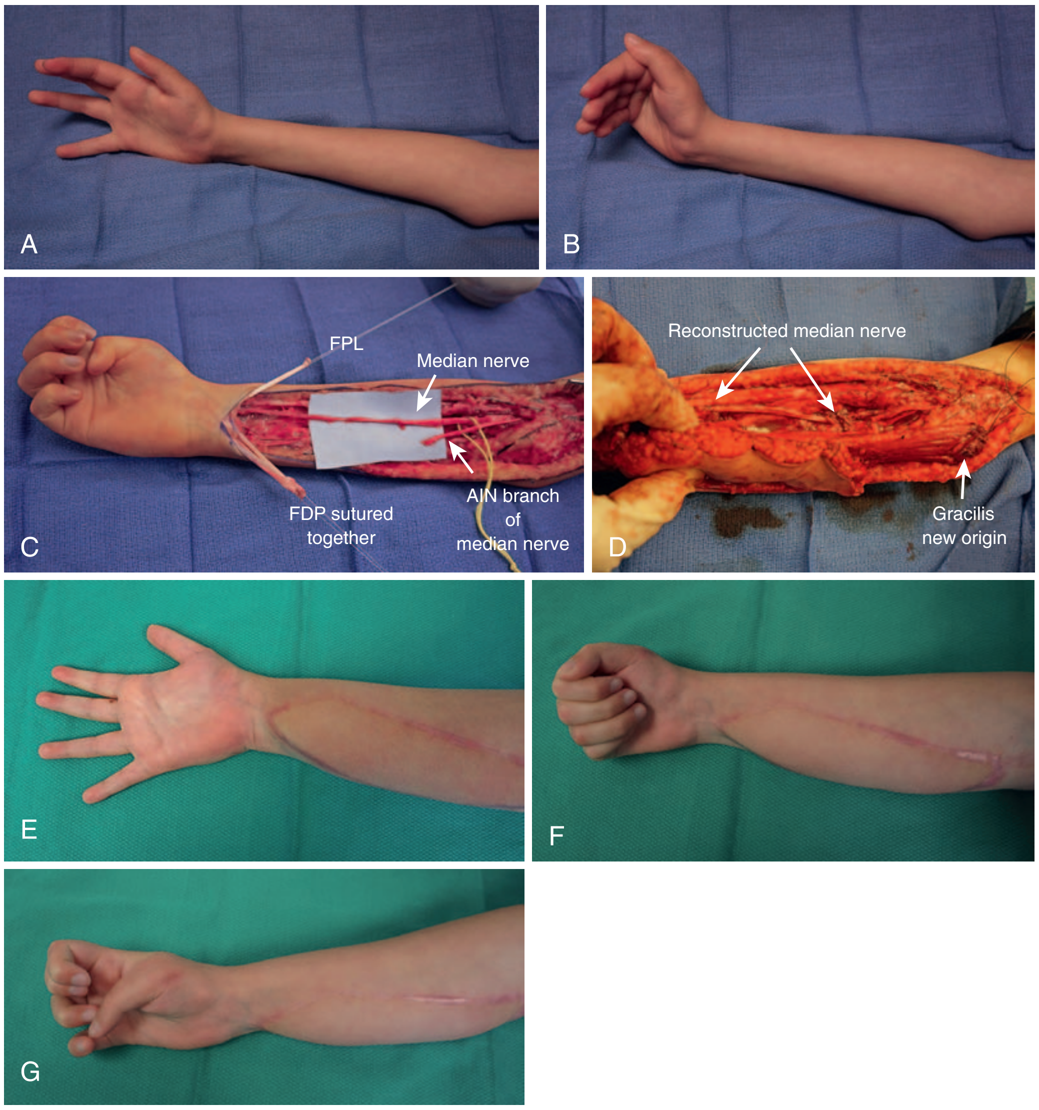
s0365 **Nerve Dysfunction Associated With Forearm Compartment**
p1410 **Syndrome.** Intrinsic dysfunction in the setting of a Volkmann ischemic contracture of the forearm results from nerve ischemia in the forearm. Intrinsic dysfunction remains an extremely difficult problem to address both operatively and nonoperatively. Nerve reconstruction is performed when there is absent sensory and motor function or a clearly necrotic nerve is identified at the time of exploration. Some recovery of sensation can be expected. Motor recovery is less predictable. There are few available tendon transfers for functional restoration because donor tendons are often necessary for extrinsic flexor reconstruction. If protective sensation is not improved with neurolysis or nerve reconstruction, nerve transfer from the dorsal sensory branch of the radial nerve to the ulnar digital nerve of the thumb and radial digital nerve of the index finger should be considered for restoration of sensate pinch. Also, if ulnar nerve function is intact, transfer of the common digital nerve to the fourth web space to the radial digital nerve of the index finger and ulnar digital nerve of the thumb is another option for sensory restoration for pinch.

Volkmann Contracture of the Hand s0370

Volkmann contracture isolated to the hand is much less p1415 common than contracture in the forearm. Little is written about this problem, and treatment options are limited. Volkmann contracture of the hand commonly involves contracture of the first web space with the inability to open the thumb for grasp. The fingers assume variable degrees of the intrinsic-plus posture, with metacarpophalangeal joint flexion and proximal interphalangeal joint extension secondary to ischemia within the interosseous muscles. In combination with the thumb deformity, the hand cannot be opened sufficiently to grasp even medium-sized objects (Figure 51.20).

The first web space contracture is addressed with excision p1420 of the first dorsal interosseous muscle and the fibrotic portion of the adductor pollicis. Options to maintain the web space include placement of a bone block from the iliac crest between the thumb and index metacarpal shafts, or fusion of the

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051



f0100

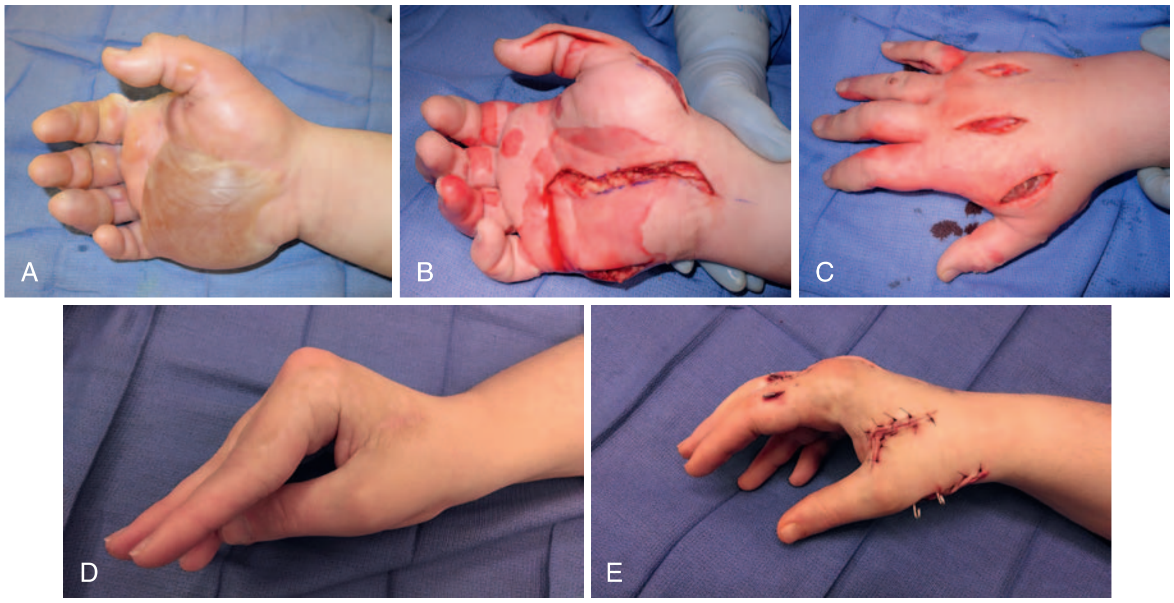
FIGURE 51.19 This 5-year-old boy developed a Volkmann contracture after sustaining a supracondylar humerus fracture. One year after his initial injury, he underwent a flexor origin slide to reduce wrist and finger flexion contractures. One year later he underwent a free functional muscle transfer of the gracilis for restoration of finger flexion. The extensor carpi radialis longus was transferred to restore flexor pollicis longus function. An opponensplasty was performed 9 months later using the extensor indicis proprius. **A,** Preoperative extension 1 year after flexor origin slide. **B,** Preoperative flexion. **C,** Necrotic flexor muscles have been partially resected. The flexor digitorum profundus tendons are sutured together distally. The flexor pollicis longus tendon has been independently separated. The median nerve has been dissected. The anterior interosseous nerve (AIN) branch has been isolated for neurorrhaphy to the nerve to the gracilis. **D,** Insetting of functional free gracilis muscle. The median nerve has been reconstructed with a sural nerve graft over a 7-cm segment. **E,** Finger and wrist extension at 1 year after functional free gracilis transfer and median nerve reconstruction. **F,** Finger and thumb flexion at 1 year after his last surgery. **G,** Opposition to small finger at 1 year. See Video 51.3. *AIN,* Anterior interosseous nerve; *FDP*, flexor digitorum profundus; *FPL*, flexor pollicis longus.

trapeziometacarpal joint. If skin is deficient, these procedures may require augmentation with a four-flap “Z”-plasty, pedicled rotational flap, or even free tissue transfer. Our preferred technique would be dependent upon the extent of contracture. The choice of free tissue transfer would depend on the body habitus of the patient, but a posterior interosseous forearm rotational flap or a free lateral arm flap would be our first choice. Sacrifice of the index finger with a ray resection may be a good alternative for some patients, particularly those with substantial dysfunction of the index finger. This provides an adequate web space for grasp, removes the need for tissue transfer, and allows the resected index metacarpal to be used as a bone block between the first and third metacarpals to maintain the web space.

Intrinsic tightness of the fingers clinically presents as a metacarpophalangeal joint flexion and interphalangeal joint extension. Intrinsic tightness can sometimes be distinguished from joint contracture by performing an intrinsic tightness test. p1425

Milder cases of intrinsic contracture can be addressed with excision of portions of the oblique and lateral bands at the level of the distal third of the proximal phalanx.[40,54,77] Fixed joint contractures are addressed with concomitant capsulectomy and collateral ligament releases as needed. Intrinsic muscle sliding procedures have been described but have limited indications p1430

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051



f0105 **FIGURE 51.20** A 38-year-old diabetic presented to the orthopedic department more than 24 hours after lying on his hand for an unknown period of time during a diabetic coma. **A,** Appearance of the hand at time of presentation. **B,** Fasciotomy performed immediately after presentation, volar incisions. **C,** Fasciotomy performed immediately after presentation, dorsal incisions. **D,** Volkmann contracture of the hand developed despite release. **E,** First web space release with excision of fibrotic muscles and release of the intrinsics to the index and long fingers at the level of the metacarpophalangeal joint.

with severe contractures. These muscle sliding procedures have better outcomes with some underlying intrinsic muscle function preservation. Tenolysis of the flexor and extensor tendons and release of the intrinsic muscles at their insertion may be necessary to treat severe contractures. Despite these extensive releases, overcorrection of the contracture is not typically seen.

p1435 There is a limited role for tendon transfers in treatment of these deformities. Tendon transfers such as the flexor digitorum superficialis (ring finger) or extensor indicis proprius for reconstruction of opposition may improve function after addressing the contracture.

s0385 **Complications**

p1490 Complications can be seen with any surgical procedures. Specific complications related to surgery for Volkmann contracture are listed below.

s0390 ***Complications of Tendon Transfer.*** The most difficult aspect of
p1495 performing a tendon transfer is establishing the appropriate tension of the transfer. Overtensioning or undertensioning can limit the functional outcome. Incorrect tensioning can be addressed with secondary surgery to tighten or loosen the transfer.

s0395 ***Complications of Flexor Origin Slide.*** Hematoma formation and
p1500 wound dehiscence are potential complications. The use of a drain and judicious closure will minimize these complications. Sharma and Swamy reported on 19 patients with two events of wound dehiscence that healed by secondary intention.[75]

s0400 ***Complications of Functional Free Muscle Transfer.*** FFMT is a
p1505 complex procedure associated with multiple potential complications, which can be divided into acute and long-term complications and also into those at donor sites and those at recipient sites.

p1510 *Acute complications at the recipient site* include flap loss, partial flap loss (either skin paddle or partial muscle loss),

CRITICAL POINTS ***Late Management of Volkmann Contracture*** b0040

Pitfalls and Their Prevention s0375

- Distinguishing Volkmann contracture from pseudo–Volkmann contracture is important: p1440
  Historical features may favor one diagnosis over the other; clinical findings of nerve involvement are less likely in pseudo–Volkmann contracture; magnetic resonance imaging will not show ischemic muscle changes in pseudo–Volkmann contracture u0820
- Failure to address severe muscle necrosis with wide excision of necrotic or fibrotic muscle may result in nerve ischemia and contracture: When necrotic and/or fibrotic muscle is identified, early excision of it and reconstruction of the compartment with healthy soft tissue will limit scarring and ischemia of the nerves u0825
- Progressive or recurrent deformity during growth: regardless of the treatment provided this will occur. Night splinting should be continued through skeletal maturity u0830
- Flexor-pronator slide: (1) Incomplete correction at the time of surgery will not improve postoperatively with therapy; obtain maximum correction during surgery; (2) injury to the common interosseous artery (which supplies the dorsal forearm compartment) can be prevented by careful dissection, especially in the proximal third of the forearm u0835
- Free functional muscle transfer: (1) With prolonged surgical ischemia (>2 hours), even if the muscle survives, muscle function will likely be poor; consider a second muscle transfer; (2) therapy that is too aggressive during the early stage of healing can lead to rupture of muscle fibers; use gentle rehabilitation for the first 6 months following FFMT u0840

Common Complications s0380

- If the deformity recurs after a soft tissue procedure, arthrodesis of the wrist may be necessary and may need to be combined with proximal row carpectomy p1475
- Inadequate active range of motion or strength after flexor origin slide may need to be managed with FFMT u0850

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051

hematoma, and infection. *Long-term complications at the recipient site* include scarring and tendon adhesions requiring revision surgery, attenuation at the tendon repair site, and inadequate recovery of muscle power for the desired level of function. In pediatric patients, the bone growth may be more rapid than the transferred muscle growth, which can lead to joint contracture.

p1515 *Acute complications at the donor site* include hematoma or seroma formation. The latissimus dorsi donor site is frequently complicated by seroma formation. Quilting and use of fibrin sealant at the donor site may reduce this complication.[4] Drains are a prerequisite to lessen this complication and should be retained until the patient is ambulating and drain output is less than 25 mL in 24 hours. Several authors have reported transient peroneal or sciatic nerve palsy related to intraoperative positioning.[1,23] *Long-term donor site complications* include painful unsightly scarring, donor site pain or dysesthesia, and functional losses. Russell and colleagues investigated changes in shoulder girdle function following latissimus dorsi harvest, noting a 5% to 10% decrease in shoulder girdle strength.[71] Deutinger and colleagues measured a decrease in adductor strength of 11% following harvest of the gracilis muscle.[23] Despite the measured decrease in muscle strength, the relative weakness is rarely noted by the patient, and therefore this possibility is not a contraindication for donor selection.

p1590 **For Case Studies, Videos, and more, please visit ExpertConsult.com.**

REFERENCES

1. Addosooki AI, Doi K, Hattori Y: Technique of harvesting the gracilis for free functioning muscle transplantation. *Tech Hand Up Extrem Surg* 10(4):245–251, 2006.
2. Allen M, Barnes M: Chronic compartment syndrome of the flexor muscles in the forearm: a case report. *J Hand Surg [Br]* 14(1):47–48, 1989.
3. Bae D, Kadiyala R, Waters P: Acute compartment syndrome in children: contemporary diagnosis, treatment, and outcome. *J Pediatr Orthop* 21(5):680–688, 2001.
4. Bailey SH, Oni G, Guevara R, et al: Latissimus dorsi donor-site morbidity: the combination of quilting and fibrin sealant reduce length of drain placement and seroma rate. *Ann Plast Surg* 68(6):555–558, 2012.

4a. Bardenheuer L: Die entstehung und behandlung der ischaemishen muskelkontractur und gangran. *Dtsch Z Chir* 108:44, 1911.

4b. Bebawy JF, Gupta DK, Koht A: Compartment syndrome caused by a properly functioning infusion pump. *J Clin Anesth* 23(2):134–136, 2011.

5. Becker MH, Wermter TB, Brenner B, et al: Comparison of clinical performance, histology and single-fiber contractility in free neurovascular muscle flaps. *J Reconstr Microsurg* 16(7):525–534, 2000.
6. Blakemore L, Cooperman D, Thompson G, et al: Compartment syndrome in ipsilateral humerus and forearm fractures in children. *Clin Orthop Relat Res* 376:32–38, 2000.
7. Boody AR, Wongworawat MD: Accuracy in the measurement of compartment pressures: a comparison of three commonly used devices. *J Bone Joint Surg Am* 87(11):2415–2422, 2005.
8. Botte MJ, Fronek J, Pedowitz RA, et al: Exertional compartment syndrome of the upper extremity. *Hand Clin* 14(3):477–482, 1998.
9. Branco BC, Inaba K, Barmparas G, et al: Incidence and predictors for the need for fasciotomy after extremity trauma: a 10-year review in a mature level I trauma centre. *Injury* 42(10):1157–1163, 2011.

9a. Brooks B: Pathologic changes in muscle as a result of disturbances of circulation. *Arch Surg* 5:188–216, 1922.

9b. Brooks B: New methods for study of the diseases of the circulation of the extremities. *J Bone Joint Surg Am* 7:316–318, 1925.

10. Brown JS, Wheeler PC, Boyd KT, et al: Chronic exertional compartment syndrome of the forearm: a case series of 12 patients treated with fasciotomy. *J Hand Surg Eur Vol* 36(5):413–419, 2011.
11. Buchbinder D, Karmody AM, Leather RP, et al: Hypertonic mannitol: its use in the prevention of revascularization syndrome after acute arterial ischemia. *Arch Surg* 116(4):414–421, 1981.
12. Burkhalter W, Christensen RC, Brown P: Extensor indicis proprius opponensplasty. *J Bone Joint Surg Am* 55(4):725–732, 1973.
13. Bywaters EG: 50 years on: the crush syndrome. *BMJ* 301(6766):1412–1415, 1990.
14. Cho MS, Rinker BD, Weber RV, et al: Functional outcome following nerve repair in the upper extremity using processed nerve allograft. *J Hand Surg [Am]* 37(11):2340–2349, 2012.
15. Choi PD, Melikian R, Skaggs DL: Risk factors for vascular repair and compartment syndrome in the pulseless supracondylar humerus fracture in children. *J Pediatr Orthop* 30(1):50–56, 2010.
16. Chuang D-C: Functioning free-muscle transplantation for the upper extremity. *Hand Clin* 13(2):279–289, 1997.
17. Chuang D-C, Carver N, Wei F-C: A new strategy to prevent the sequelae of severe Volkmann's ischemia. *Plast Reconstr Surg* 98(6):1023–1031, 1996.
18. Chuang DC, Carver N, Wei FC: A new strategy to prevent the sequelae of severe Volkmann's ischemia. *Plast Reconstr Surg* 98(6):1023–1031, 1996.
19. Clay NR, Dent CM: Limitations of pulse oximetry to assess limb vascularity. *J Bone Joint Surg Br* 73(2):344, 1991.
20. Cole AL, Herman RA, Jr, Heimlich JB, et al: Ability of near infrared spectroscopy to measure oxygenation in isolated upper extremity muscle compartments. *J Hand Surg [Am]* 37(2):297–302, 2012.
21. Collinge C, Kuper M: Comparison of three methods for measuring intracompartmental pressure in injured limbs of trauma patients. *J Orthop Trauma* 24(6):364–368, 2010.
22. Dente CJ, Feliciano DV, Rozycki GS, et al: A review of upper extremity fasciotomies in a level I trauma center. *Am Surg* 70(12):1088–1093, 2004.
23. Deutinger M, Kuzbari R, Paternostro-Sluga T, et al: Donor-site morbidity of the gracilis flap. *Plast Reconstr Surg* 95(7):1240–1244, 1995.
24. Doi K, Sakai K, Ihara K, et al: Reinnervated free muscle transplantation for extremity reconstruction. *Plast Reconstr Surg* 91(5):872–883, 1993.

24a. Domanasiewicz A, et al: Modified Colzi method in the management of established Volkmann contracture—the experience of Trzebnica Limb Replantation Center (preliminary report). *Ortop Traumatol Rehabil* 10(1):12–25, 2008.

25. Duckworth AD, Mitchell SE, Molyneux SG, et al: Acute compartment syndrome of the forearm. *J Bone Joint Surg Am* 94(10):e63, 2012.
26. Ebraheim NA, Abdelgawad AA, Ebraheim MA, et al: Bedside fasciotomy under local anesthesia for acute compartment syndrome: a feasible and reliable procedure in selected cases. *J Orthop Traumatol* 13(3):153–157, 2012.
27. Eichler G, Lipscomb P: The changing treatment of Volkmann's ischemic contractures from 1955-1965 at the Mayo Clinic. *Clin Orthop Relat Res* 50:215–223, 1967.
28. Farber A, Tan TW, Hamburg NM, et al: Early fasciotomy in patients with extremity vascular injury is associated with decreased risk of adverse limb outcomes: a review of the National Trauma Data Bank. *Injury* 43(9):1486–1491, 2012.
29. Flynn J, Bashyal RK, Yeger-McKeever M, et al: Acute traumatic compartment syndrome of the leg in children: diagnosis and outcome. *J Bone Joint Surg Am* 93: 937–941, 2011.
30. Franz RW, Skytta CK, Shah KJ, et al: A five-year review of management of upper-extremity arterial injuries at an urban level I trauma center. *Ann Vasc Surg* 26(5): 655–664, 2012.
31. Garcia-Mata S: Chronic exertional compartment syndrome of the forearm in adolescents. *J Pediatr Orthop* 33(8):832–837, 2013.
32. Garfin SR, Mubarak SJ, Evans KL, et al: Quantification of intracompartmental pressure and volume under plaster casts. *J Bone Joint Surg Am* 63(3):449–453, 1981.
33. Garr JL, Gentilello LM, Cole PA, et al: Monitoring for compartmental syndrome using near-infrared spectroscopy: a noninvasive, continuous, transcutaneous monitoring technique. *J Trauma* 46(4):613–616, 1999.
34. Goldner J: Volkmann's ischemic contracture. In Flynn J, editor: *Hand surgery*, New York, 1975, Williams & Wilkins, pp 599–618.

34a. Gosset J: [Surgical desinsertion of the anterior long muscles of the forearm in the treatment of contractures and ischemic retraction]. *J Chir* 72(5):487–494, 1956.

35. Goubier J, Saillant G: Chronic compartment syndrome of the forearm in competitive motor cyclists: a report of two cases. *Br J Sports Med* 37:452–454, 2003.

35a. Griffiths D: Volkmann's ischaemic contracture. *Br J Surg* 28:239–260, 1940.

36. Grottkau B, Epps H, Di Scala C: Compartment syndrome in children and adolescents. *J Pediatr Surg* 40(4):678–682, 2005.
37. Gulgonen A: Invited Review Article: Surgery for Volkmann's ischaemic contracture. *J Hand Surg [Br]* 26(4):283–296, 2001.
38. Hammerberg EM, Whitesides TE, Jr, Seiler JG, 3rd: The reliability of measurement of tissue pressure in compartment syndrome. *J Orthop Trauma* 26(1):24–31, 2012.
39. Hargens A, Schmidt D, Evans K, et al: Quantitation of skeletal muscle necrosis in a model compartment syndrome. *J Bone Joint Surg Am* 63(4):631–636, 1981.
40. Harris C, Jr, Riordan DC: Intrinsic contracture in the hand and its surgical treatment. *J Bone Joint Surg Am* 36:10–18, 1954.

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051

41. Harrison JW, Thomas P, Aster A, et al: Chronic exertional compartment syndrome of the forearm in elite rowers: a technique for mini-open fasciotomy and a report of six cases. *Hand* 8(4):450–453, 2013.
41a. Hill RL, Brooks B: Volkmann's ischemic contracture in hemophilia. *Ann Surg* 103(3):444–449, 1936.
41b. Holden C: Compartmental syndromes following trauma. *Clin Orthop Rel Res* 113:95–102, 1975.
42. Holden C: The pathology and prevention of Volkann's ischaemic contracture. *J Bone Joint Surg Br* 61(3):296–300, 1979.
43. Hope M, McQueen M: Acute compartment syndrome in the absence of fracture. *J Orthop Trauma* 18(4):220–224, 2004.
44. Hovius S, Ultee J: Volkmann's ischemic contracture. prevention and treatment. *Hand Clin* 16(4):647–657, 2000.
44a. Hwang R, Bas de Witte P, Ring D: Compartment syndrome associated with distal radial fracture and ipsilateral elbow injury. *J Bone Joint Surg Am* 91:642–645, 2009.
45. Ikuta Y, Kubo T, Tsuge K: Free muscle transplantation by microsurgical technique to treat severe Volkmann's contracture. *Plast Reconstr Surg* 58(4):407–411, 1976.
45a. Jepson P: Ischaemic contracture. Experimental study. *Ann Surg* 84(6):785–793, 1926.
46. Kalyani B, Fisher B, Roberts C, et al: Compartment syndrome of the forearm: a systematic review. *J Hand Surg [Am]* 36:535–543, 2011.
47. Kim DH, Han K, Tiel RL, et al: Surgical outcomes of 654 ulnar nerve lesions. *J Neurosurg* 98(5):993–1004, 2003.
48. Kim DH, Kam AC, Chandika P, et al: Surgical management and outcomes in patients with median nerve lesions. *J Neurosurg* 95(4):584–594, 2001.
49. Kozin S: *Supracondylar elbow fractures, in ASSH specialty day 2012. Make my day in hand surgery*, San Francisco, 2012, American Society for Surgery of the Hand.
50. Krimmer H, Hahn P, Lanz U: Free gracilis muscle transplantation for hand reconstruction. *Clin Orthop Relat Res* 314:13–18, 1995.
51. Kumar PR, Jenkins JP, Hodgson SP: Bilateral chronic exertional compartment syndrome of the dorsal part of the forearm: the role of magnetic resonance imaging in diagnosis: a case report. *J Bone Joint Surg Am* 85:1557–1559, 2003.
52. Lanz U, Felderhoff J: Ischaemische kontrakturen an unterarm und hand. *Handchir Mikrochir Plast Chir* 32:6–25, 2000.
53. Lee CH, Lee KH, Lee SH, et al: Chronic exertional compartment syndrome in adductor pollicis muscle: case report. *J Hand Surg [Am]* 37(11):2310–2312, 2012.
54. Littler JW: The finger extensor system. Some approaches to the correction of its disabilities. *Orthop Clin North Am* 17(3):483–492, 1986.
55. Liu XY, Ge BF, Win YM, et al: Free medial gastrocnemius myocutaneous flap transfer with neurovascular anastomosis to treat Volkmann's contracture of the forearm. *Br J Plast Surg* 45(1):6–8, 1992.
55a. Manktelow R, McKee N: Free muscle transplantation to provide active finger flexion. *J Hand Surg [Am]* 3(5):416–426, 1978.
55b. Manktelow R, Zucker R: The principles of functioning muscle transplantation: applications to the upper arm. *Ann Plast Surg* 22(4):275–282, 1989.
56. Mars M, Hadley GP: Failure of pulse oximetry in the assessment of raised limb intracompartmental pressure. *Injury* 25(6):379–381, 1994.
57. Matsen FA, 3rd: Compartmental syndrome. A unified concept. *Clin Orthop Relat Res* 113:8–14, 1975.
58. McQueen M, Gaston P, Court-Brown C: Acute compartment syndrome. Who is at risk? *J Bone Joint Surg Br* 82:200–203, 2000.
59. Mubarak SJ, Carroll NC: Volkmann's contracture in children: aetiology and prevention. *J Bone Joint Surg Br* 61:285–293, 1979.
60. Murovic JA: Upper-extremity peripheral nerve injuries: a Louisiana State University Health Sciences Center literature review with comparison of the operative outcomes of 1837 Louisiana State University Health Sciences Center median, radial, and ulnar nerve lesions. *Neurosurgery* 65(4 Suppl):89, 2009.
61. Nisbet NW: Volkmann's ischaemic contracture benefited by muscle slide operation. *J Bone Joint Surg Br* 34(2):245–247, 1952.
62. Oredsson S, Plate G, Qvarfordt P: The effect of mannitol on reperfusion injury and postischaemic compartment pressure in skeletal muscle. *Eur J Vasc Surg* 8(3):326–331, 1994.
63. Ouellette E, Kelly R: Compartment syndromes of the hand. *J Bone Joint Surg Am* 78(10):1515–1522, 1996.
64. Page C: An operation for the relief of flexion-contracture in the forearm. *J Bone Joint Surg Am* 3:233–234, 1923.
64a. Pavanini G, Volpe A: [Diaphysary resection using Colzi's method in the treatment of Volkmann's syndrome]. *Clin Ortop* 26:287–292, 1975.
65. Prasarn ML, Ouellette EA: Acute compartment syndrome of the upper extremity. *J Am Acad Orthop Surg* 19(1):49–58, 2011.
66. Ragland RI, Moukoko D, Ezaki M, et al: Forearm compartment syndrome in the newborn: report of 24 cases. *J Hand Surg [Am]* 30(5):997–1003, 2005.
67. Reigstad A, Hellum C: Volkmann's ischaemic contracture of the forearm. *Injury* 12(2):148–150, 1981.
68. Rolands R, Lond M: A case of Volkmann's contracture treated by shortening of the radius and ulna. *Lancet* 2:1168–1171, 1905.
69. Ronel D, Mtui E, Nolan W, III: Forearm compartment syndrome: analysis of surgical approaches to the deep space. *Plast Reconstr Surg* 114(3):697–705, 2004.
70. Royle SG: Compartment syndrome following forearm fracture in children. *Injury* 21(2):73–76, 1990.
71. Russell RC, Pribaz J, Zook EG, et al: Functional evaluation of latissimus dorsi donor site. *Plast Reconstr Surg* 78(3):336–344, 1986.
72. Scaglietti O: Chirurgische behandlung der volkmannschen paralyse. *Verh Dtsch Orthop Ges* 45:219, 1957.
73. Seddon H: Volkmann's ischaemia. *Br Med J* 1(5398):1587–1592, 1964.
74. Seddon HJ: Volkmann's contracture: treatment by excision of the infarct. *J Bone Joint Surg Br* 38:152–174, 1956.
75. Sharma P, Swamy MK: Results of the Max Page muscle sliding operation for the treatment of Volkmann's ischemic contracture of the forearm. *J Orthop Traumatol* 13(4):189–196, 2012.
76. Simpson NS, Jupiter JB: Delayed onset of forearm compartment syndrome: a complication of distal radius fracture in young adults. *J Orthop Trauma* 9(5):411–418, 1995.
77. Smith RJ: Balance and kinetics of the fingers under normal and pathological conditions. *Clin Orthop Relat Res* 104:92–111, 1974.
78. Soderberg TA: Bilateral chronic compartment syndrome in the forearm and the hand. *J Bone Joint Surg Br* 78(5):780–782, 1996.
79. Staudt JM, Smeulders MJ, van der Horst CM: Normal compartment pressures of the lower leg in children. *J Bone Joint Surg Br* 90(2):215–219, 2008.
80. Steinmann SP, Bishop AT: Chronic anconeus compartment syndrome: A case report. *J Hand Surg [Am]* 25(5):959–961, 2000.
81. Summerfield SL, Folberg CR, Weiss AP: Compartment syndrome of the pronator quadratus: a case report. *J Hand Surg [Am]* 22(2):266–268, 1997.
82. Sundararaj GD, Mani K: Management of Volkmann's ischaemic contracture of the upper limb. *J Hand Surg [Br]* 10(3):401–403, 1985.
83. Tan TW, Joglar FL, Hamburg NM, et al: Limb outcome and mortality in lower and upper extremity arterial injury: a comparison using the National Trauma Data Bank. *Vasc Endovascular Surg* 45(7):592–597, 2011.
84. Tiidus PM: Is intramuscular pressure a valid diagnostic criterion for chronic exertional compartment syndrome? *Clin J Sport Med* 24(1):87–88, 2014.
85. Tsuge K: Treatment of established Volkmann's contracture. *J Bone Joint Surg Am* 57(7):925–929, 1975.
86. Tsuge K: Management of established Volkmann's contracture. In Green D, editor: *Green's operative hand surgery*, ed 4, Philadelphia, 1999, Churchill Livingstone, pp 592–603.
87. Ultee J, Hovius SE: Functional results after treatment of Volkmann's ischemic contracture: a long-term followup study. *Clin Orthop Relat Res* 431:42–49, 2005.
87a. Volkmann R: Die ischaemischen muskellaehmungen und kontrakturen. *Centrabl f Chir* 51:801, 1881.
88. Waterman BR, Laughlin M, Kilcoyne K, et al: Surgical treatment of chronic exertional compartment syndrome of the leg: failure rates and postoperative disability in an active patient population. *J Bone Joint Surg Am* 95(7):592–596, 2013.
89. Whitesides T, Haney T, Mounoto K: Tissue pressure measurments as a determinant for the need of fasciotomy. *Clin Orthop Relat Res* 113:43, 1975.
90. Wilder R, Magrum E: Exertional compartment syndrome. *Clin Sports Med* 29:429–435, 2010.
91. Winkes MB, Luiten EJ, van Zoest WJ, et al: Long-term results of surgical decompression of chronic exertional compartment syndrome of the forearm in motocross racers. *Am J Sports Med* 40(2):452–458, 2012.
92. Xing-yan L, Bao-feng G, Yi-Min W, et al: Free medial gasrocnemius myocutaneous flap transfer with neurovascular anastomosis to treat Volkmann's contracture of the forearm. *Br J Plast Surg* 45:6–8, 1992.
93. Yuan P, Pring M, Gaynor T, et al: Compartment syndrome following intramedullary fixation of pediatric forearm fractures. *J Pediatr Orthop* 24(4):370–375, 2004.
94. Zancolli E: Classification of established Volkmann's ischemic contracture and the program for its treatment. In Zancolli E, editor: *Structural and dynamic bases of hand surgery*, Philadelphia, 1979, JB Lippincott.
95. Zuker R, Egerszegi E, Manktelow R, et al: Volkmann's ischemic contracture in children: the results of free vascularized muscle transplantation. *Microsurgery* 12:341–345, 1991.
96. Zuker RM: Volkmann's ischemic contracture. *Clin Plast Surg* 16(3):537–545, 1989.
97. Zuker RM, Bezuhly M, Manktelow RT: Selective fascicular coaptation of free functioning gracilis transfer for restoration of independent thumb and finger flexion following Volkmann ischemic contracture. *J Reconstr Microsurg* 27(7):439–444, 2011.
98. Zuker RM, Manktelow RT: Functioning free muscle transfers. *Hand Clin* 23(1):57–72, 2007.

ISBN: 978-1-4557-7427-2; PII: B978-1-4557-7427-2.00051-4; Author: Wolfe & Pederson & Hotchkiss & Kozin & Cohen; 00051