21 Compartment Syndrome in the Upper Limb

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21.1 Introduction

Compartment syndromes occur when pressures within a fascial compartment overcome the intravascular pressures required to perfuse the soft tissues contained within the compartment [1]. Compartment syndromes fall into two main categories: ***acute compartment syndrome*** **(ACS)** and ***exertional compartment syndrome*** **(ECS)**. ACS is a surgical emergency and must be addressed rapidly to minimize tissue death. In the upper limb, a missed diagnosis or delayed treatment can produce devastating consequences such as Volkmann contracture of the forearm and loss of limb. ECS can be *acute* (AECS) or *chronic* (CECS) and is far less common than ACS. ECS does not typically present as a surgical emergency, rather, patients with ECS will describe progressive pain during physical activity that resolves after cessation of the activity. With ECS, increased intracompartmental pressure (ICP) occurs during sustained activity and produces pain; however, the etiology and pathophysiology of ECS in the upper limb remain poorly understood [1].

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21.2 Anatomy

Separated by the elbow, the upper limb is divided into the brachium proximally, and the forearm distally. The ***brachium*** is divided into two fascial compartments: the **anterior compartment** and the **posterior compartment** (Table 21.1). The muscles of the anterior compartment are all innervated by the musculocutaneous nerve, except for the brachialis, which has duel innervation, receiving radial nerve innervation to its lateral portion. The arterial blood supply for the anterior compartment is from the brachial artery. The median, ulnar, radial, and medial and lateral antebrachial cutaneous nerves all course distally within the anterior compartment, which places these structures at risk for ischemia during a compartment syndrome [2]. Both muscles of the posterior compartment are innervated by the radial nerve, and their blood supply comes from the profunda brachii artery.

Compared to the brachium, the ***forearm*** is more anatomically complex, and has three fascial compartments: the **volar** (flexor), **dorsal** (extensor), and **lateral** (mobile wad) compartments (Table 21.2). Additionally, the volar and dorsal compartments are each subdivided into ***superficial*** and ***deep*** sub-compartments. The interosseous membrane that spans between the radius and ulna bones separates the volar and dorsal compartments of the forearm. Distally,

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Table 21.1 Anatomy of the compartments of the brachium

Brachial compartments	Muscles	Innervation	Arterial supply
Anterior compartment	Coracobrachialis	Musculocutaneous	Brachial artery
	Biceps brachii		
	Brachialis	Musculocutaneous and radial	
Posterior compartment	Triceps brachii	Radial	Profunda brachii
	Anconeus		

Table 21.2 Anatomy of the compartments of the forearm

Forearm compartments		Muscles	Innervation	Arterial supply
Volar (flexor) compartment	Superficial	Pronator teres	Median	Ulnar and radial arteries
		Palmaris longus		
		Flexor digitorum superficialis		
		Flexor carpi radialis		
		Flexor carpi ulnaris	Ulnar	
	Deep	Flexor digitorum profundus	Median and ulnar	
		Flexor pollicis longus	Median	
		Pronator quadratus		
Dorsal (extensor) compartment	Superficial	Extensor digitorum communis	PIN	Radial artery branches and posterior interosseous artery
		Extensor carpi ulnaris		
		Extensor digiti minimi		
	Deep	Abductor pollicis longus		
		Extensor pollicis brevis		
		Extensor pollicis longus		
		Extensor indicis		
		Supinator		
Lateral (mobile wad) compartment		Brachioradialis	Radial	
		Extensor carpi radialis longus	Radial	
		Extensor carpi radialis brevis	PIN	

the carpal tunnel is continuous with the volar compartment and is frequently affected in ACS of the forearm.

21.3 Pathophysiology

The most common etiology associated with development of ACS in adults is high energy trauma with long bone fractures. ACS is commonly associated with supracondylar humerus fractures (SCHF), both-bone radius and ulna forearm fractures (BBFF), and with floating elbow injuries (combination of SCHF and BBFF) in children [3]. Fractures are the most common cause of ACS; however, acute compartment syndrome can result from a variety of injuries to the upper limb (Table 21.3). The deep volar compartment is the most commonly affected, while the mobile wad is generally the least affected.

ACS occurs when there is elevated pressure within a fibro-osseous space which ultimately results in decreased tissue perfusion [4]. After an initial insult to the forearm and/or brachium, swelling ensues and ICP rises. This leads to an early collapse of thin-walled venules, which results in decreased venous outflow. Arterioles will remain patent longer due to their muscular-walled composition, which allows them to withstand greater pressures. As ICP continues to rise, the imbalance of inflow and outflow within the compartment increases. As venous outflow obstruction progresses and ICP rises, ultimately, arterial inflow will become obstructed and soft tissue ischemia ensues.

Table 21.3 Causes of compartment syndromes in the upper limb

Type	Causes
Constrictive	Tight dressings, casts, or splints Tourniquet Patient "found down"/prolonged compression Amniotic band syndrome (in utero)
Intracompartmental fluid extravasation	Penetrating trauma Crush injury High pressure injection injury Fracture hematoma Vascular injury Regional anesthesia Bleeding disorders Reperfusion injury Extravasation of IV infiltrate
Inoculation	Spider bite Snakebite Needle injection (intravenous drug abuse)
Other	Infection Burns Suction injury

As ICP increases, if left unchecked, it will eventually become greater than capillary pressure. At the capillary level, microcirculation ceases when ICP is equal to or greater than diastolic blood pressure (DBP). When this threshold has been reached, the microcirculation providing perfusion to the muscle, nerve, and vascular tissue is decreased, which ultimately causes cell death [5]. The pressure gradient between DBP and ICP is represented as ΔP (termed "delta P"), and the equation $\Delta P = \text{DBP} - \text{ICP}$ is used to determine the pressure gradient and thus perfusion capability of a compartment. A canine study demonstrated that when ICP rose to within 20 mmHg of DBP, or when $\Delta P = 20$ mmHg, muscle necrosis resulted [5]. For this reason, a threshold of $\Delta P \leq 30$ mmHg is used frequently as a cutoff to help guide the decision-making process of when to perform surgery while monitoring a potential compartment syndrome. Because of the difficultly and inconsistency of ICP monitoring, and the vasomotor instability that is common during trauma scenarios, some institutions use ICP pressure monitoring devices with an ICP >30–40 mmHg as a threshold for fasciotomy. Whether using ΔP or ICP to guide treatment, one fact is undisputed and is represented well by the commonly used phrase ***"time is muscle,"*** as muscle necrosis can occur within 4 h in the setting of sustained elevated compartment pressures [6].

There are several theories regarding the pathophysiology of chronic exertional compartment syndrome (CECS). In some patients, ICP rises as muscles swell during activity, which can produce pain, weakness, and sensory paresthesias. The main difference between CECS and ACS is that, with CECS, cessation of the activity that produces the symptoms typically leads to a resolution of the symptoms. CECS of the forearm has been associated with motorcycle sports, and the majority of reported cases involve bilateral forearms. Cessation of the activity will reverse the pathophysiology of CECS so loss of limb and function are uncommon; however, it is still possible to produce irreversible damage if an individual continues the activity despite pain [1].

Acute exertional compartment syndrome (AECS) has also been described but is not well understood. AECS should be suspected when a patient presents with prolonged pain out of proportion to examination after strenuous activity. The majority of research on AECS focuses on the lower extremity. A case series that looked at AECS in the lower extremity found that patients with longer than 24 h of symptoms prior to fasciotomies had substantial muscle necrosis and functional deficit after surgery [7]. One unusual case report describes a weightlifter with bilateral supraspinatus AECS which required surgical release 1 day after a strenuous upper body workout [8]; however, the reported incidence of AECS in the upper extremity is rare [9].

21.4 Physical Examination

The clinical examination for ACS is classically taught using the "6 P's" mnemonic. Pain with passive flexion or extension of the hand, wrist, or elbow, pressure, pallor, pulselessness, paralysis, and paresthesias. Although easy to memorize as a medical student, this classic teaching aid may result in missed or delayed treatment of ACS as it provides no insight into the timing and relative importance of the individual presenting signs. Pulselessness, for example, is typically a ***late sign*** of advanced ACS and occurs after irreversible damage to soft tissues has already taken place. Additionally, pallor, paralysis, and paresthesias are nonspecific signs that may have no relation to elevated intracompartmental pressure.

When examining a patient with potential ACS, the surgeon needs to know the earliest signs of impending trouble so that fasciotomy can be performed before irreversible damage has occurred. The most important early findings on physical exam are: **(1) Pain with passive stretch of the affected compartment, (2) Pain out of proportion to exam, and (3) Pressure with palpation of the affected compartment that worsens over time.**

It is quite helpful to have multiple time points of physical examination so that pressures and a patient's pain responses can be trended as worsening or improving. Additionally, it is important to note that these physical exam findings can vary with different stages of presentation. Pain generally peaks around 2–6 h of ischemia and appears to improve as nerve function deteriorates [10]. This means a "burned-out" compartment syndrome that has already produced muscle and nerve death will typically present as less painful than an early compartment syndrome. It is also important to consider distracting injuries when assessing pain.

Young children are not typically able to accurately report pain, so ACS will likely present differently in the pediatric population. Due to the unreliability of the "6 P's" when examining children, the "3 A's" should be used instead. These are: **(1) increasing need for Analgesia, (2) presence of Anxiety, and (3) progressive Agitation (crying)** [3] (Table 21.4). The physician should maintain a high index of suspicion for ACS in children with these symptoms.

Table 21.4 The "3 P's" and "3 A's"

Adults: "3 P's"	Children: "3 A's"
Pain with passive stretch	Analgesia requirement increasing
Pain out of proportion	Anxiety
Pressure with palpation	Agitation

In contrast to physical examination findings with ACS, the physical examination for a patient with CECS may be normal in a clinic setting. To elicit symptoms, patients with CECS require a dynamic examination that takes place during the physical activity that produces the symptoms. CECS symptoms typically evolve and worsen during prolonged activity and may persist for some time after cessation of the activity [11].

21.5 Clinical Decision-Making

ACS is a surgical emergency and the potential consequences of delayed or missed treatment can be devastating. In essence, "time is muscle," and early release will give the best chance for preservation of viable soft tissue and functional return after recovery. In the case of ACS, solving the "who" and "when" in the equation can be far more challenging than the "how" of surgical compartment release. A physician's ability to accurately examine a patient for ACS, and a well-honed clinical threshold for surgical release, are the two most important factors when determining how to proceed with the treatment for ACS.

Frequent and clear communication between the surgeon, medical trainees, and nursing staff involved in the patient's care is critical and must be prioritized for optimal outcomes. Serial examination by the same provider or team is useful when monitoring progression of symptoms. Compartment pressure monitoring is helpful when treating obtunded patients who are not able to participate in an examination, or for objective information when the clinical examination is equivocal. However, if there is a high clinical suspicion for ACS, fasciotomy should not be delayed.

CECS is generally not a surgical emergency. Patients will report exertional pain that prevents them from continuing activities, and cessation of the activity will produce a resolution of symptoms. With more chronic presentations of CECS, patients may notice a decrease in endurance and performance over time [1]. Elective fasciotomy of the affected compartment(s) may be performed for persistent pain that limits activity.

21.6 Technique: ICP measurement

There are several methods and techniques for measuring and monitoring intracompartmental pressure. When indicated, we prefer the Stryker Intra-Compartmental Pressure Monitor System (Stryker Instruments; Kalamazoo, MI USA) (Fig. 21.1). The Pressure Monitor is assembled with three disposable items that are then used to obtain ICP. ICP should be taken within 5 cm of a fracture or site of injury as ICP is typically highest in this location. When monitoring a forearm for compartment syndrome, it is not always clear which compartment is affected. In this scenario, measurements taken from the volar compartment are most commonly affected due to a higher muscle volume than the dorsal compartment or mobile wad and typically report the highest pressure. The effects of gravity on pooling blood can falsely alter ICP [12], so the forearm should be at the level of the heart and motion should be limited while obtaining measurements. In some intensive care situations, it may be beneficial to monitor ICP continuously. Multiple techniques utilizing arterial transducers have been shown to be effective for this purpose [4, 13].

In addition to a careful and accurate history and physical examination, intracompartmental pressure measurements obtained during provocative maneuvers is the gold standard for diagnosis of ECS. To establish a baseline, a patient's ICP is first measured at rest (<10 mmHg is a normal resting ICP for the forearm). Serial measurements are then taken after the patient performs the activity that causes their symptoms. Meeting one or more of the following criteria is diagnostic for ECS: **(1) Pre-exercise pressure ≥10 mmHg, (2) ICP reaches ≥20 mmHg at 1 or 5 min after exercise, (3) ICP takes longer than 15 min to return to <10 mmHg**. When measuring forearm compartments, the superficial volar compartment as well as the dorsal compartment should be measured [1]. Although some authors suggest releasing each compartment that meets 2 or more of the above criteria, intracompartmental pressure measurements during and after dynamic examination in the clinic setting may be technically challenging and inaccurate. For this reason, some authors recommend relying on history and physical examination alone, foregoing provocative testing, for the diagnosis of ECS [11].

21.6.1 Imaging

Several studies have evaluated the utility of magnetic resonance imaging (MRI) as a diagnostic

Fig. 21.1 ***Left***: Intracompartmental pressure monitoring device components (**a**) device housing/digital display, (**b**) side-ported, non-coring needle, (**c**) diaphragm chamber, (**d**) syringe; ***Right:*** Assembled device. (Stryker Instruments; Kalamazoo, MI USA)

tool for CECS [11, 14]. Tominaga et al. performed pre- and post-exertional forearm MRI before and after fasciotomies. To initiate forearm ECS, patients used a hand gripping device for 10 min or until onset of symptoms prior to MRI. Before fasciotomy, increased muscle signal on T2-weighted MRI was present. This signal resolved on repeat MRI after fasciotomies were performed. MRI has been shown to have utility as a non-invasive method of evaluating for increased ICP, this technology is not always available and may be cost-prohibitive for many patients.

21.7 Operative Technique: Compartment Fasciotomy in the Upper Limb

21.7.1 Volar Forearm and Anterior Brachium

In a cadaver study, Ronel et al. reviewed the anatomy and evaluated techniques for forearm compartment release to determine the safest approach. They showed that an ulnar approach to the deep volar compartment, between the flexor carpi ulnaris (FCU) and flexor digitorum superficialis (FDS), is the safest approach.

To perform an anterior fasciotomy, a volar skin incision is made radial to FCU at the wrist and extended to the medial epicondyle. When fasciotomy of the anterior compartment of the brachium is indicated, the forearm incision can be extended across the elbow between brachioradialis and biceps brachii proximally to connect with a standard deltopectoral incision Additionally, because the volar compartment is continuous with the carpal tunnel, the median nerve is at high risk for ischemia during ACS of the volar forearm compartment and carpal tunnel release should be performed (Figs. 21.2 and 21.3).

When crossing the elbow during forearm and brachial fasciotomies, it is important to release the lacertus fibrosus as this can act as a point of compression for the brachial artery and median nerve as they cross into the forearm (Fig. 21.4).

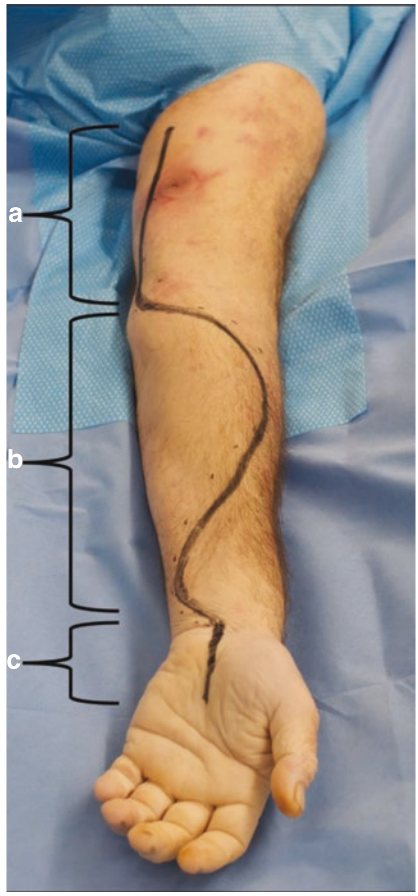

Fig. 21.2 Fasciotomy incisions drawn for the (**a**) anterior brachium, (**b**) volar forearm, and (**c**) carpal tunnel. *(Copyright Benjamin Graves, MD)*

21.7.2 Dorsal Forearm, Mobile Wad, and Posterior Brachium

A midline approach between the extensor digitorum communis (EDC) and the extensor carpi radialis brevis (ECRB) is safe for fasciotomy of the dorsal compartment. The dorsal incision extends from the lateral epicondyle to the distal

Fig. 21.3 Fasciotomy of the anterior brachium, volar forearm, and carpal tunnel. *(Copyright Benjamin Graves, MD)*

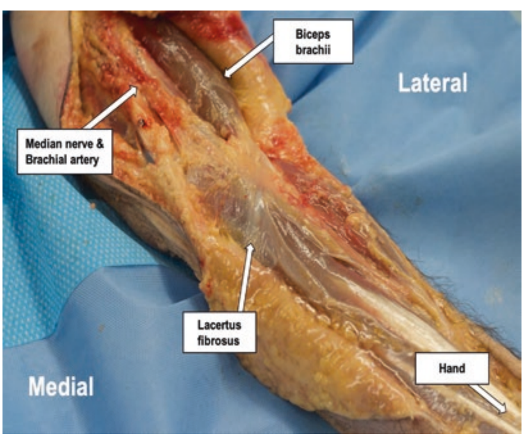

Fig. 21.4 The *lacertus fibrosus* crosses from the biceps brachii musculotendinous junction laterally to the medial flexor pronator muscle mass. This thick band of tissue can act as a point of compression for the anterior neurovascular structures that cross the elbow and should be released. *(Copyright Benjamin Graves, MD)*

Fig. 21.5 (**a**) Incision drawn for dorsal forearm compartment releases, and (**b**) after fasciotomy of the mobile wad and dorsal compartments. (*Copyright Benjamin Graves, MD)*

radioulnar joint. This will allow access to both the mobile wad and the extensor fascial compartments [15] (Fig. 21.5).

When fasciotomy of the posterior compartment of the brachium is indicated, a midline skin incision made over the posterior arm is safe and provides access to the fascia of the triceps brachii. The anconeus is typically indirectly decompressed following release of the triceps fascia (Fig. 21.6).

After skin incision, a 15-blade knife is used to perforate the fascial sleeve. A Metzenbaum scissor is then used to run this fascial rent proximally and distally, until there are no points of muscle tenting, and the muscle is free to expand. Ischemic muscle is debrided until only healthy muscle remains.

Operative technique for compartment release in CECS is similar to above; however, fascial release is targeted to the affected compartment

Fig. 21.6 Posterior view of a left arm, with the patient's head to the right, after fasciotomy of the posterior brachial compartment. *(Copyright Benjamin Graves, MD)*

and is typically performed in an elective setting with smaller incisions than are required for ACS. Preoperative evaluation helps determine which compartment will benefit from release [1].

21.8 Post-Operative Management: When to Close

Following fasciotomy for ACS, in the setting of muscle necrosis, patients should be taken back to the operating room for serial debridement until no necrotic tissue is found. Patients often require several trips to the operating room prior to final closure. After swelling abates, if primary closure is not achievable, split-thickness skin grafting is performed to cover healthy muscle and fat.

In the absence of muscle necrosis, the skin is taught after compartment fascial release all incisions should be left open following decompression. However, it is often the case that the skin can be approximated after fasciotomy without undue tension. When this is the case, the skin may be closed over the released fascial compartment. The authors prefer closure in this setting with 2–0 or #0 nylon suture utilizing a vertical mattress configuration. A moist dressing can be applied if the fasciotomy wound is left open, or alternatively, a negative pressure vacuum dressing can be applied. A negative-pressure vacuum dressing will aid in minimizing retraction of the wound edges and maintaining egress of edema fluid from the wound, which will aid in infection control and, ultimately, wound closure. Negative-pressure wound vacuum dressings can also be applied to a fasciotomy incision after the incision has been closed. This so-called incisional vac will help granulation tissue form, will help control wound edema leakage, and will help minimize the requirement for dressing changes.

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