# Chapter 6
# Limitations of Pressure Measurement


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In 1975, Matsen identified increased compartment pressure as the unifying and central pathogenic factor in compartment syndrome [1]. At that same time, Whitesides published a method for tissue pressure measurement [2]. While pressure is an important factor in compartment syndrome, the more important factor is cellular ischemia. Tissue ischemia is the critical factor in compartment syndrome, but at present we do not have a method of assessing the severity and duration of tissue ischemia. Compartment pressure measurement has therefore been used as a surrogate measure of tissue ischemia.

While many clinicians believe the diagnosis of compartment syndrome is a clinical diagnosis based on injury history and physical examination findings, there are circumstances in which compartment pressure measurement is a useful adjunct diagnostic test. These include patients in whom a clinical exam is not feasible or is not reliable such as the unresponsive patient with associated high-risk injuries. Compartment pressure measurement is also typically recommended when a patient's clinical examination findings are unclear. This could include a situation where motor paralysis or sensory changes are present due to a direct nerve injury. Severe and increasing pain is felt to be the most important finding in diagnosing compartment syndrome, but expression of pain severity can vary greatly among patients. Compartment pressure measurement can help rule out compartment syndrome in the patient who expresses an extremely high level of pain despite a clinical scenario of an injury not suspected to result in compartment syndrome.

There are numerous limitations in the use of compartment pressure measurement to diagnose and make treatment decisions in patients at risk for compartment syn-

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drome. There is no agreement on a specific pressure value for the diagnosis of compartment syndrome. Different tissues and different individuals have a variable response to elevated compartment pressures [3]. Measurement of a single pressure does not allow a clinician to assess the degree of ischemia, since the time course of pressure elevation is unknown. In addition, measurement inaccuracies are common due to technical errors, and pressures can vary greatly based on the location of the measurement with respect to the fracture location. Therefore, most authors indicate that pressure measurements must be correlated with the clinical situation and physical examination findings.

## The Problem of Defining a Pressure Measurement Threshold Value

Various absolute pressure measurements were initially recommended as a threshold for the diagnosis of compartment syndrome. In 1978, Mubarak recommended an absolute threshold value of 30 mm Hg [4]. He based this value on the findings that normal muscle capillary pressure is 20–30 mm Hg in cats and dogs, and because clinically pain and paresthesia first appeared around 30 mm Hg in patients undergoing tibial osteotomy. The authors noted that when compartment pressure is >30 mm Hg, capillary pressure is not sufficient to maintain muscle capillary blood flow, stating that, "We believe therefore that it is prudent to use a value close to the capillary blood pressure (20–25 mm Hg) as a criteria for decompression." While the authors recommended 30 mm Hg as a threshold, they did note that there is no single correct pressure for all individuals. They also noted that some of their patients with pressures of 30–40 mm Hg might well have recovered without fasciotomy. They further indicated that, "A spectrum of critical pressure exists depending on many variables, including the measurement technique used."

A higher absolute pressure threshold of 45 mm Hg was suggested by a clinical study of 30 patients at risk for compartment syndrome in which it was noted that all patients who had maximum compartment pressures of 45 mm Hg or less did not require fasciotomy and demonstrated no residual of a missed compartment syndrome at follow-up [5]. The authors noted that, "Perhaps the most significant observation in this series of patients was that individuals varied in their tolerance for increased tissue pressure. Thus, there was a range of intracompartmental pressures in which some patients demonstrated neuromuscular deficits while others did not." The authors indicated that they currently used a tissue pressure in excess of 45 mm Hg as a *relative* indication for surgical decompression, assuming a normal blood pressure, blood volume, and peripheral vascular system, but also noted that these indications must be tempered by the patient's overall condition and the trend of the symptoms, signs, and pressure measurements. The authors highlighted the difficulty in selecting an absolute threshold value for fasciotomy, noting that, "The concept of a critical pressure above which surgical decompression should be performed is of limited value. If a low value is selected as a critical pres-

sure, all patients with significant compartmental syndromes would certainly be included. Yet it is likely that surgery would be performed in a number of patients who would have no significant functional losses without such intervention."

Whitesides introduced the concept of a differential pressure threshold that is widely accepted today. He noted that in the clinical use of pressures, the compartment pressure should be evaluated in association with the patient's diastolic blood pressure [2]. Note that, "Ischemia begins when pressures rises to within 10–30 mm Hg of the diastolic blood pressure. Fasciotomy should usually be performed when the tissue pressure rises to within 10–30 mm Hg of the diastolic pressure in a patient with any of the other signs or symptoms of a compartmental syndrome." This concept of differential threshold helps explain the variable tolerance in absolute pressures noted by other authors. A patient with an elevated diastolic pressure can tolerate a greater elevation in compartment pressure without experiencing ischemia, while a hypotensive patient may develop tissue ischemia with a much lower elevation of their compartment pressure.

McQueen and Court Brown monitored the anterior compartment pressures in a prospective study of 116 patients with tibial fractures using an indwelling slit catheter and followed them to look for sequelae of missed compartment syndrome [6]. Three patients whose differential pressure was <30 mm Hg required a fasciotomy. They reported that had an absolute pressure value of 30 mm Hg been used, 43% of the patients would have had an unnecessary fasciotomy. Using a differential threshold pressure ($\Delta P$) of <30 mm Hg compared to the patient's diastolic blood pressure as the indication for fasciotomy resulted in no cases of missed compartment syndrome. However, the actual duration of the decreased differential threshold pressure in the 3 patients that underwent fasciotomy was not clearly stated. In a larger retrospective series of 850 patients, McQueen and colleagues reported on their use of a differential pressure threshold of <30 mm Hg ($\Delta P < 30$ mm Hg) for greater than 2 hours as the criteria for diagnosis of compartment syndrome [7]. The diagnosis of compartment syndrome was considered to be correct if surgeons noted the escape of muscles at fasciotomy along with muscular color change or necrosis, while they considered the diagnosis of compartment syndrome incorrect if it was possible to primarily close the fasciotomy wounds within 48 hours of the fasciotomy. They calculated that the use of a $\Delta P < 30$ mm Hg for greater than 2 hours has a sensitivity of 94%, a specificity of 98%, a positive predictive value of 93%, and a negative predictive value of 99% for the diagnosis of compartment syndrome [7].

In contrast, Janzing and Broos performed a prospective study of 95 patients in which they measured the anterior compartment pressures for 24 hours in 95 consecutive patients with tibial fractures and followed the patients for 1 year [8]. Eighteen patients were found to have developed compartment syndrome, including 14 patients that underwent fasciotomy and 4 patients that were found to have residual symptoms at follow-up such as toe contractures, hypoesthesia, and muscle weakness. They found wide overlap in the values of the differential pressure between patients with and without the diagnosis of compartment syndrome. While 19% of patients were diagnosed with compartment syndrome, had they used a $\Delta P$ of <30 mm Hg, 45.4% of patients would have been diagnosed with compartment

syndrome. They found wide overlap in the values of the differential pressure between patients with and without the diagnosis of compartment syndrome. These authors concluded that there did not seem to be a threshold value with an acceptable combination of specificity and sensitivity for the diagnosis of compartment syndrome and cautioned that using a $\Delta P < 30$ mm Hg could result in unnecessary fasciotomies. The authors noted the dilemma faced when identifying a threshold for the diagnosis of compartment syndrome using pressure measurement. They could choose a criterion with high specificity but that would risk missing patients with a compartment syndrome, or they could choose a criterion with high sensitivity which would result in patients undergoing unnecessary fasciotomies.

## The Problem of a Single Pressure Measurement

A single measurement of compartment pressure with a single data point provides only limited information. It does not provide information about what the pressure was in prior hours, and it does not predict what the pressure may be during subsequent hours. As such, a single elevated pressure measurement may not accurately reflect the presence or duration of any actual ischemic changes within a compartment.

Investigators studied 46 patients with 48 tibial fractures without clinical suspicion of compartment syndrome and measured pressure in all four compartments after the induction of anesthesia [9]. They did not perform any fasciotomies regardless of the pressure measurements, and at 6 months postoperatively, none of the patients displayed evidence of a missed compartment syndrome. When they compared the compartment pressure measurements with the patient's preoperative diastolic blood pressure, 35% of cases had a $\Delta P < 30$ mm Hg. Twenty-four percent of cases had a $\Delta P < 20$ mm Hg, and 22% had absolute pressure > 45 mm Hg, yet none of these patients underwent fasciotomy and none developed sequela of a missed compartment syndrome. These investigators concluded that a one-time measurement of compartment pressure overestimates the rate of compartment syndrome and may lead to unnecessary fasciotomy. Using the criteria of $\Delta P < 30$ mm Hg in patients without clinical symptoms to diagnose compartment syndrome would lead to a 35% false-positive rate.

O'Toole and colleagues have reported a wide variation in the rate of diagnosis and treatment of compartment syndrome among academic traumatologists practicing at the same level I trauma center [10]. In a review of 386 patients with tibia fractures, the diagnosis of compartment syndrome between different surgeons ranged from 2% to 24% ($p < 0.005$). Equally noteworthy was that a similar variation was seen in the surgeon's use of compartment pressure measurement, which seemed to approximately parallel their rate of compartment syndrome diagnosis. While this study did not examine the medicolegal aspects of compartment syndrome, there is a general sense that once compartment pressures are measured, there is a low threshold for proceeding with a fasciotomy.

## The Problems of Measurement Accuracy

Numerous studies have examined the accuracy of compartment pressure measurement. These studies have examined the type of needle used, the technique, and the location of pressure measurement.

Investigators compared three types of needles in a canine mode of acute compartment syndrome [11]. Needles tested included a standard end bore needle, a side-posted needle, and a slit catheter. A concern regarding the use of a standard bore needle is that a soft tissue plug within the needle can prevent accurate pressure measurement. They found no statistical difference between slit catheter and side-ported needle. However, standard end bore needle measurements were consistently higher than the other two methods ($p < 0.001$).

Overestimation of compartment pressure measurements with standard end bore needles was also confirmed in another study [12]. This study, which compared use of a commercial pressure monitor (Stryker, Mahwah, NJ), arterial line monitor, and the technique using IV tubing as described by Whitesides, found that the Whitesides technique had the highest standard errors and provided clinically unacceptable scatter in its measurements.

Dr. Whitesides rebutted the reported unacceptable reliability with a standard bevel-tipped needle and the Whitesides technique, stating that this finding was contrary to his cumulative clinical and research experience. He indicated that when properly used with a small required saline flush to assure a fluid continuum between tissue and the pressure monitor, this technique had acceptable accuracy [13]. They performed simultaneous testing of three different devices (slit catheters, side ported needles, and standard 18-gauge end bore bevel-tipped needles) in the same area of fusiform muscle against increasing intramuscular pressure using the same transducer and monitor and reported that the side-ported needle, slit catheter, and standard 18-gauge bevel-tipped needle were statistically equivalent.

In his original description of compartment pressure measurement, Whitesides used a 1.25 mm capillary tube, while current technique typically uses IV tubing that has an internal diameter of 3 mm. This difference in diameter makes it more difficult to differentiate a flat versus a convex versus a concave fluid meniscus during the pressure measurement. when using the 3 mm internal diameter IV tubing. If an electronic transducer is not available for pressure measurement, Whitesides and colleagues recommended averaging several consecutive saline measurements.

Investigators have also highlighted technical problems associated with the measurement of compartment pressures [14]. In this study, a consistent model of lower leg compartment syndrome was created in cadaveric specimens. Thirty-eight physicians, including residents, fellows, and attending physicians, were observed while they measured the four compartments of the lower leg using a commercial compartment pressure measurement device. Only 31% of the measurements were performed using the correct technique. In 39% of the measurements, there were minor errors in the technique. Minor errors included failure to maintain the angle of insertion

after zeroing, failure to use the proper amount of saline for flushing, and inconsistent zeroing between each measurement. In the remaining 30% of measurements, participants made catastrophic errors. These included failure to properly assemble the components of the monitor, not flushing the air from the syringe/transducer apparatus, failure to zero the monitor before insertion, zeroing the monitor under the skin, and failure to insert the needle into the correct anatomic space.

Of the 31% of measurements performed using the correct technique, only 60% were with 5 m Hg of the known compartment pressure. Of the 39% of measurements made with minor errors in technique, only 42% were with 5 m Hg of the known compartment pressure. Of the 30% of measurements made with catastrophic errors, only 22% were with 5 m Hg of the known compartment pressure.

The investigators concluded that errors are common in compartment pressure measurement. While proper technique improved accuracy, only 60% of these measurements were with 5 m Hg of the known compartment pressure. Given their findings, the investigators cautioned that measurement accuracy should not be assumed and reported measurements viewed as within a range of values rather than as an absolute value.

Another group of investigators compared three measurement methods in 26 patients with suspected compartment syndrome, measuring 97 muscle compartments in 31 injured limbs. The measurement methods used were a modification of Whitesides' needle manometer technique using a straight 18-gauge needle with a central venous pressure monitor, an electronic transducer-tipped catheter (Depuy Synthes, West Chester, PA), and a solid-state transducer intracompartmental catheter (Stryker, Mahwah NJ) [15]. The overall intraclass correlation coefficient for the three methods was 0.83 (range 0.77–0.88), indicating only satisfactory agreement. The mean difference among measurements in each compartment was 8.3 mm Hg (range 0–51 mm Hg), while 27% showed major differences that exceeded 10 mm Hg. The authors concluded that the methods were similar but not completely reliable for measuring compartment pressure. They emphasized that while all methods appeared useful as aids in diagnosis of compartment syndrome, compartment pressure data, especially single readings, must be interpreted in view of clinical findings. They recommended that no single pressure measurement be used as the primary determinant in individual decisions for or against fasciotomy and emphasized that specific values must be considered in the context of the patients' overall clinical picture.

Another factor that influences the measured compartment pressure value is the location of the measurement with respect to the fracture. Compartment pressures were measured at the level of the fracture and at 5 cm increments proximally and distally in 25 consecutive patients with closed tibial fractures [16]. The peak compartment pressure was usually found at the level of the fracture and was always located within 5 cm of the fracture site. The measured pressures decreased progressively at increasing distances proximal and distal to the site of the highest pressure measurement. Most notably, decreases of 20 mm Hg were common just 5 cm adjacent to the site of the highest pressure measurement.

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