Diagnostic Techniques in Acute Compartment Syndrome of the Leg

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INTRODUCTION

Acute compartment syndrome (ACS) is a clinical condition characterized by the increase of pressure within a closed anatomic space, resulting in a lack of local perfusion to the tissues within this space.¹⁻³ If untreated, the lack of perfusion results in irreversible damage to the tissues in the affected compartment. The results of an unrecognized or untreated compartment syndrome of the leg include pain, paralysis, paresthesia, and muscle necrosis with possible rhabdomyolysis. The potential disability associated with a neglected compartment syndrome is usually irreversible.

Compartment syndrome has been reported in a wide variety of traumatic and nontraumatic clinical scenarios. The most common injury resulting in a compartment syndrome is a fracture of the tibial diaphysis due to relatively high incidence of this fracture and the anatomic environment of closed fascial spaces found in this area.¹,³⁻⁴,⁶ This differentially affects young active individuals.⁷⁻⁸ Permanent disability in this particular group of patients can place a large burden on the individual, society, and, often, our medicolegal system.⁹⁻¹⁰

The reported incidence of compartment syndrome varies due to differing diagnostic criteria, sampling methods, and patient populations.¹⁻³,⁵⁻¹¹ Reported incidence of compartment syndrome after tibial fractures ranges from 1.2% to 30.4%.⁵⁻¹² The incidence is greater in men and in those younger than 35 years. Thirty-six percent of all compartment syndromes occur after tibial diaphyseal fractures.⁷ Fractures of the tibial plateau only develop a compartment syndrome in 3% of cases.⁴

Treatment of a compartment syndrome consists of immediate and complete fasciotomy of all fascial compartments involved. In the leg, this involves all 4 anatomic compartments. Wounds are left open for a minimum of 48 hours or until the compartment syndrome is resolved. Direct closure of the fasciotomy wounds is attempted; however, plastic surgical techniques are often required. Delay in the diagnosis or treatment of the syndrome results in permanent disability. Therefore, the ability to diagnose a compartment syndrome in a timely manner, before the onset of irreversible ischemic changes, is crucial to prevent permanent disability.³,⁵,¹³

The first sign of a compartment syndrome is excessive pain disproportionate to the severity of injury in an at-risk patient. If untreated, paresthesia and paralysis occur. The timing between these symptoms is variable.⁴ Clinical examination of the patient reveals palpable tightness, an increase in pain on passive stretch of the compartment involved, progressive paresthesia, and eventually paralysis. The clinical picture is variable and often only a few signs are present.

CURRENT STATE OF THE ART

Objective: To review the efficacy of the current diagnostic methods of acute compartment syndrome (ACS) after leg fractures.

Data Sources: A Medline (PubMed) search of the English literature extending from 1950 to May 2007 was performed using “compartment syndromes” as the main key word. Also a manual search of orthopaedic texts was performed.

Study Selection and Extraction: The results were limited to articles involving human subjects. Of 2605 primary titles, 489 abstracts limited to compartment syndromes in the leg and 577 articles related to the diagnosis of compartment syndromes were identified and their abstracts reviewed. Further articles were identified by reviewing the references. Sixty-six articles were found to be relevant to diagnostic techniques for compartment syndrome in the leg and formed the basis of this review.

Conclusions: Early diagnosis of an ACS is important. Despite its drawbacks, clinical assessment is still the diagnostic cornerstone of ACS. Intracompartmental pressure measurement can confirm the diagnosis in suspected patients and may have a role in the diagnosis of this condition in unconscious patients or those unable to cooperate. Whitesides suggests that the perfusion of the compartment depends on the difference between the diastolic blood pressure and the intra-compartmental pressure. They recommend fasciotomy when this pressure difference, known as the Δp, is less than 30 mm Hg. Access to a precise, reliable, and noninvasive method for early diagnosis of ACS would be a landmark achievement in orthopaedic and emergency medicine.

Key Words: compartment syndromes, leg injuries, tibial fractures, diagnosis, diagnostic methods

Observation of a patient with a developing compartment syndrome can lead to a delay in diagnosis and treatment. This delay possibly contributes to permanent disability. Ischemic contracture complicating tibial fractures has been estimated to occur in up to 2% of cases. Only 13% of patients with paralysis at the time of their diagnosis recover from this impairment.

Health-related quality of life is reported to be decreased after compartment syndrome of the leg. Giannoudis et al reported a significant detriment in health-related quality of life, as measured by the EQ-5D (EuroQol) tool, in patients who had undergone fasciotomy and required a skin graft or those who had longer closure times. Vandervelpen et al showed that 1 in 4 patients undergoing leg fasciotomies reported late functional disabilities. Fitzgerald et al, who reported on the sequelae of fasciotomy wounds, found symptoms related to the skin wounds in up to 77% of patients who had undergone fasciotomy of the upper or lower limb.

**DIAGNOSIS**

Little debate exists as to the necessity of a thorough and immediate fasciotomy once a compartment syndrome has been diagnosed. Nor is there disagreement when a clear presentation of clinical signs of compartment syndrome is present in a high-risk patient. However, diagnosis is often difficult in patients who cannot give a clear history or participate in a rigorous clinical examination. This includes children, those with concomitant neurological injury, the critically ill, and patients under prolonged general anesthesia. In these patients, intracompartmental pressure measurements have been used to screen for the development of compartment syndrome when clinical examination is either unreliable or equivocal. Several methods have been investigated as possible diagnostic adjuncts in the early identification of an ACS. A reliable screening tool to diagnose a developing compartment syndrome would provide the opportunity to intervene early and avoid the sequelae of a delayed diagnosis. Although further investigation is needed, several of these techniques show promise (Fig. 1).

**Pressure Measurements**

Whitesides et al were the first to apply compartment pressure measurement to the diagnosis of ACS. Since then, several techniques have been described, each with limitations that restrict their reliability or practical use. These include the needle manometer, the wick catheter, and the slit catheter. The Stryker intra-compartmental pressure monitor system (STIC) has become popular as a handheld portable device that is easily used in a variety of settings without the need for complex equipment. Continuous pressure monitoring is available by attaching a reliable catheter to an arterial transducer system. This allows a continuous readout of the pressure in the compartment and allows us to observe changes over time. Although there is some technical learning required for its accurate use, compartment pressure measurements have been successfully used clinically as an adjunct to clinical examination.

Traditionally, the diagnosis of a compartment syndrome has been on clinical criteria, with objective pressure measurements used as an adjunct for equivocal cases because the clinical picture is rarely complete. The pressure threshold that is diagnostic of compartment syndrome has been debated at length. Experts have advocated fasciotomy for absolute

![Diagram](image-url)

**FIGURE 1.** This algorithm shows the application of ACS diagnostic methods based on ACS pathophysiological stages.
compartment pressures from 30 to 45 mm Hg. This threshold for diagnosis is likely too aggressive and subjects more patients unnecessarily to fasciotomy and the risks associated with it. McQueen et al. have shown that an increase in compartment pressure after tibial nailing is expected even without the development of a frank compartment syndrome. Whitesides et al. astutely suggest that the perfusion of the compartment depends on the difference between the patient’s blood pressure and the compartment pressure and recommends fasciotomy when the compartment pressure rises to within 30 mm Hg of the diastolic blood pressure, known as the \( \Delta p \) (<30 mm Hg). White et al. have shown that an elevated intramuscular pressure alone is not diagnostic of a compartment syndrome after tibial intramedullary nailing as long as the \( \Delta p \) remains greater than 30 mm Hg. The use of the \( \Delta p \) has been consistently shown to be a more reliable indicator of the conditions necessary to produce a compartment syndrome than the compartment pressure alone. It also allows a more reflective measure in patients with abnormal physiology, such as shock or hypertension.

One difficulty encountered in the development of pressure thresholds for the diagnosis of compartment syndrome is the lack of gold standard diagnostic criteria for the condition. A collection of clinical symptoms and signs in experienced hands serves as the diagnostic criteria in most circumstances. Attempts to objectify the diagnosis for purposes of validation of measurement techniques have been made but are not universally accepted. These include the bulging of muscle compartments on fasciotomy, and second, clinical follow-up looking for the sequelae of the syndrome. The first of these is often dismissed as nonspecific, and the latter does not allow the identification of successfully treated cases.

Some authors have argued that because a rise in compartment pressure must occur before the development of a compartment syndrome, an objective pressure measurement can diagnose a compartment syndrome before the onset of symptoms and before the development of irreversible sequelae of the syndrome. Thus, fasciotomy based on continuous pressure measurements for the “impending” compartment syndrome should be the most appropriate treatment so long as the measurements are adequately sensitive and specific to the development of a full compartment syndrome. This approach has been shown to be effective in clinical practice by McQueen et al. who reported that no compartment syndromes were missed in a large prospective series using a \( \Delta p \) of <30 mm Hg as the diagnostic criteria for its presence. Despite the apparent success reported by McQueen et al., continuous pressure monitoring has not become the standard treatment in most centers. Recently, a prospective randomized trial has attempted to evaluate the addition of continuous pressure monitoring to current clinical diagnostic criteria. The recent development of a handheld fiber-optic transducer system that uses a unicrystaline piezoelectric semiconductor has eliminated some of the practical concerns of calibration and blockage that occurred frequently with catheter-based systems.

**Biomarkers**

The traumatic injury associated with tibial fractures and ACS result in the early onset of inflammatory markers. Generalized inflammatory biomarkers such as an elevated white blood cell count or a positive erythrocyte sedimentation rate cannot specifically indicate the occurrence of a compartment syndrome. Creatine kinase (CK), myoglobin (Mb), and fatty acid–binding protein (FABP) are low–molecular mass cytoplasmic proteins present in the myocardial muscles and skeletal muscles. These proteins have been introduced as plasma markers for the early detection of myocardial infarction, but at the same time, each of them show similar plasma release curves after skeletal muscle injury and necrosis. After skeletal muscle injury, both MB and FABP concentration significantly increase after 30 minutes, whereas CK concentration reaches a maximum after 2 hours. Both MB and FABP return to the baseline values at 24 hours after injury, whereas CK remains elevated for at least 48 hours.

There is no report of a coenzyme or a biomarker specific to skeletal muscle ischemia to date. Detection of a sensitive and specific biomarker for skeletal muscle ischemia that is not influenced by inflammation or tissue injury from trauma would be a tremendous accomplishment in diagnosis of ACS. Therefore, more investigation is required.

**Magnetic Resonance Imaging**

Magnetic resonance imaging (MRI) is able to detect soft tissue edema and swollen compartments on T1-weighted
spine-echo images. However, MRI cannot differentiate the edema of affected muscles in a compartment syndrome from the edema of soft tissue injury after trauma. MRI can show the tissue changes in an established compartment syndrome in a very late stage but fails to identify early changes of an ACS. MRI is a sensitive and noninvasive diagnostic tool, but the role of this technology in early diagnosis and monitoring of the ACS is limited.

Ultrasound

Ultrasonography is a noninvasive diagnostic intervention that can visualize and monitor soft tissue structure and motion. Several investigators have tried to assess the geometry and echogenicity of the affected muscles for an early diagnosis of compartment syndrome by standard sonographic methods with no consistent success. A new ultrasonic intervention called pulsed phase–locked loop (PPLL) may be useful in the diagnosis of compartment syndrome. This technique was initially developed by Ueno et al as a noninvasive method to monitor intracranial pressure. The PPLL ultrasound is a low-power ultrasonic device designed to detect submicrometer displacements between the ultrasound emitter on the skin surface and any targeted tissue that can reflect the ultrasound waves. The device transmits an ultrasonic wave through the tissue via a small transducer placed on the skin surface. The depth of penetration of the ultrasound waves is set to reach a specific tissue. The transmitted waves reflect off the targeted tissue and are received by the same transducer. The PPLL ultrasound locks onto a characteristic reflection that comes from a specific tissue. PPLL ultrasound detects the very subtle movements of fascia that correspond to local arterial pulsation. These waveforms have a characteristic shape in the normal compartment. The increased Intracompartamental Pressure (ICP) during compartment syndrome causes a reduction in normal fascial displacements in response to arterial pulsation that decreases the complexity of the fascial displacement waveform. To refine its interpretation, the limitations of this method such as the effect of possible variations of fascial movements indicative of normal physiology and anatomy should be identified. As a noninvasive monitoring device, PPLL may be a promising method for the early diagnosis of ACS; however, it requires more investigation.

Scintigraphy

Scintigraphy is a radionuclide imaging intervention. A 2-dimensional image is obtained after injection of a soluble radioisotope to evaluate regional perfusion. Scintigraphy differs from most other imaging methods because it primarily shows the physiological function of the system being investigated as opposed to its anatomy. It is mostly used to study myocardial perfusion and peripheral vascular obstructions. Edwards et al have studied the efficacy of scintigraphy in the diagnosis of chronic exertional compartment syndrome (CECS). They reported a sensitivity of 80% and a specificity of 97% for detection of CECS by using 99-technetium (99Tc)-methoxyisobutilisonitrile (MIIBI) scintigraphy. They concluded that 99Tc-MIIBI can detect compartment syndromes with good positive and negative predictive values. A major strength of this method is that all compartments of leg can be monitored simultaneously. In addition, it is a simple, cheap, and minimally invasive method. The use of scintigraphy in ACS is limited by the time required to perform this type of investigation, the potential lack of specificity in the traumatized limb, and the inability to perform repeated or continuous examinations.

Laser Doppler Flowmetry

Laser Doppler flowmetry (LDF) is a well-developed technique for the real-time measurement of microvascular perfusion in tissue. This velocimetry method is based on the “Doppler effect” that describes the shift in the frequency of a sound or light wave when the wave source and/or the receiver is moving. LDF works by illuminating the tissue with low-power laser light based on local red blood cell circulation. Light from 1 optical fiber is scattered by moving red blood cells. Another optical fiber collects the backscattered light. By analyzing the differences between the reflected and returned signals, a functional image is obtained. It is a noninvasive and highly sensitive method for continuous monitoring of local blood perfusion. Despite all the advantages, only 1 study has been performed to assess the capability of this method in diagnosis of ACS. In that study, Abraham et al successfully used LDF in the diagnosis of CECS. Although there is no documented experience of using this method for the diagnosis of ACS, the technique shows potential and requires further research.

Near-Infrared Spectroscopy

The pathophysiologic mechanism in ACS is an increased ICP compromising microvascular flow within the affected compartment that leads to an acute intracompartamental hypoxia and muscle necrosis. Near-infrared spectroscopy (NIRS) is an optical technique that can determine the redox state of various light-absorbing molecules such as hemoglobin. Its function is based on the relative tissue transparency for light in the near-infrared spectrum and on the absorption changes of hemoglobin and Mb when they are in their oxygenated versus deoxygenated states. Based on the different light absorption properties, NIRS can measure the local changes in concentration of oxygenated and deoxygenated hemoglobin and perfusion in different tissues including muscle. NIRS measures the most direct pathophysiologic consequence of ACS, intracompartamental tissue oxygen levels, rather than measuring the indirect mechanism of intracompartamental pressure that may or may not result in muscle ischemia. In 1977, Jobsis used this technology for the first time to monitor cerebral and myocardial oxygenation. During the past decade, NIRS has been used to measure tissue oxygenation especially during investigations of exercise. The NIRS instrument consists of a probe and an analyzer chip. The probe contains light-emitting and light-receiving fibers.

The depth of penetration of NIRS light is about half the distance between emitter and receiver probes. Specific wavelengths can be selected for transmission and subsequent absorption of light for measuring oxygenated and deoxygenated hemoglobin. The difference between emitted and receiver infrared light signals undergo signal processing by an integrated software program to extract the tissue oxygen saturation.
value. NIRS also has the potential to measure the redox state of cytochrome c oxidase that can provide more specific information regarding intracellular oxygenation and whether the oxygen supply is sufficient to meet energy demands at the cellular level. Local ischemia causes an increased extraction of oxygen by muscular tissue that reduces the level of local venous oxyhemoglobin. NIRS can measure the changes in tissue hemoglobin saturation and thus has the potential to provide continuous noninvasive monitoring of intracompartmental ischemia and hypoxia.

Fewer studies illustrate the utility of NIRS. In a case report, Tobias and Hoernschemeyer presented the use of NIRS in monitoring intracompartmental oxygenation of a 1-month-old infant who developed an ACS of the leg after cardiac surgery. Several studies have shown high sensitivity and specificity of NIRS in the diagnosis of exertional chronic compartment syndrome, but no clinical trial is available regarding the diagnostic value of NIRS in a clinical model of ACS. In an animal model of limb ACS, Garr et al demonstrated a strong correlation between the level of oxyhemoglobin measured by NIRS and perfusion pressure in the affected muscles. Despite the promising advantages of near-NIRS as a diagnostic tool, it still has some practical limitations, such as low depth of penetration (maximum depth of 30–40 mm) and extraneous variables that could affect the penetration and reflection of the emitted infrared light signal. The system needs further technical improvements, and more clinical investigations are currently under way. NIRS may provide the benefit of a rapid, continuous, noninvasive, sensitive, and specific tool for early detection of ACS.

**Pulse Oximetry**

Pulse oximetry is a noninvasive technique that estimates the level of arterial oxygen saturation using technology based on principles somewhat similar to those of the NIRS device. The pulse oximeter emits red and infrared light that is absorbed by the different levels of oxyhemoglobin and deoxyhemoglobin during pulsatile flow. The oximeter probe measures the difference between the emitted and received red and infrared light during the diastolic and systolic phases of pulsatile flow to compute the estimated oxygen saturation. It is mainly used in clinical care units to monitor the level of hypoxemia. It cannot measure intracompartmental tissue oxygen saturation and is unable to detect intracompartmental hypoperfusion because pulse oximetry technology requires adequate pulsatile flow to compute its signal. Several reports have demonstrated that pulse oximetry is not an appropriate aid in the detection or monitoring of impaired perfusion.

**Hardness Measurement Techniques**

Several authors have described the use of quantitative hardness measurement techniques for the diagnosis of compartment syndrome. These techniques are based on the concept that skin surface pressure over a compartment can predict intracompartmental pressure. A noninvasive handheld device formulates a quantitative hardness curve of force versus depth of indentation by applying a 5-mm-diameter probe to a limb muscle compartment to estimate the ICP. Although the accuracy of this technique is not yet confirmed, improvements may enhance the usefulness of this measure as a noninvasive screening tool for ACS.

**Direct Nerve Stimulation**

Two reports have suggested using direct nerve stimulation at the site where a nerve enters the compartment in patients who are unable to voluntarily contract the muscles of a compartment. This technique can differentiate a motor dysfunction due to neuropraxia secondary to a high ICP from a primary nerve injury proximal to the compartment. The lack of muscular contraction in response to electrical stimulation of

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**FIGURE 2.** Comparison of advantages between diagnostic methods of ACS.
the compartment nerve can indicate the ACS, whereas the presence of a muscle contraction in response to the stimulation may indicate a proximal nerve injury.59 However, because paralysis is a late sign of ACS, this method is not useful for prospective monitoring of high-risk patients.

**Vibratory Sensation**

Increased ICP alters regional neural function including the perception of vibratory sensation.59 In a clinical study, Phillips et al69 demonstrated a direct correlation between impaired perception of vibration and increasing ICP. They suggested that diminished response to vibratory stimuli as measured with a 256 cycle per second tuning fork may be a useful and very early indication of a developing ACS.70 However, like other subjective measurements, it is not practical in children, in unconscious patients, or in those unable to cooperate.

**Tissue Ultrafiltration**

Tissue ultrafiltration is a technique in which small semipermeable hollow fibers are inserted into tissues for the removal of local interstitial fluid. It is primarily used as a laboratory method of assaying the interstitial space. Initially, Odland et al hypothesized that a tissue ultrafiltration device can extract local interstitial fluid directly from the involved muscles.71 Extracted fluid with a higher than expected concentration of metabolic markers of muscle ischemia may predict ACS. Further refinement of this technique in addition to identification of a specific biomarker indicative to skeletal muscle ischemia could be of some benefit to early diagnosis of ACS.

**SUMMARY**

An ACS is diagnosed by the interpretation of a collection of clinical signs and symptoms in a high-risk patient. This requires a detailed examination, a vigilant examiner, and a cooperative patient. In situations when the examination is equivocal or unreliable, objective tests that include compartment pressure monitoring can add information for clinical decision making. The early identification of compartment syndrome can significantly reduce the physical, financial, and vocational disability experienced by the injured patient. Advances in the methods, technology, and application of techniques for the early diagnosis of a compartment syndrome have renewed interest for their investigation. Serum markers of muscle damage, the measurement of changes in intracompartmental pressure, and the measurement of compartmental perfusion and ischemia provide promising opportunities for clinicians and researchers (Fig. 2). Further efforts in this area are encouraged.

**REFERENCES**