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Physicians' Ability to Manually Detect Isolated Elevations in Leg Intracompartmental Pressure

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Background: Serial physical examination is recommended for patients for whom there is a high index of suspicion for compartment syndrome. This examination is more difficult when performed on an obtunded patient and relies on the sensitivity of manual palpation to detect compartment firmness—a direct manifestation of increased intracompartmental pressure. This study was performed to establish the sensitivity of manual palpation for detecting critical pressure elevations in the leg compartments most frequently involved in clinical compartment syndrome.

Methods: Reproducible, sustained elevation of intracompartmental pressure was established in fresh cadaver leg specimens. Pressures tested included 20 and 40 mm Hg (negative controls) and 60 and 80 mm Hg (considered to be consistent with a compartment syndrome). Each leg served as an internal control, with three compartments having a noncritical pressure elevation. Orthopaedic residents and faculty were individually invited to manually palpate the leg with a known compartment pressure and to answer the following questions: (1) Is there a compartment syndrome? (2) In which compartment or compartments do you believe the pressure is elevated, if at all? (3) Describe your examination findings as soft, compressible, or firm.

Results: When a true-positive result was considered to be the correct detection of an elevation of intracompartmental pressures and correct identification of the compartment with the elevated pressure, the sensitivity of manual palpation was 24%, the specificity was 55%, the positive predictive value was 19%, and the negative predictive value was 63%. With increasing intracompartmental pressure, fasciotomy was recommended with a higher frequency (19% when the pressure was 20 mm Hg, 28% when it was 40 mm Hg, 50% when it was 60 mm Hg, and 60% when it was 80 mm Hg). When a true-positive result of manual palpation was considered to be an appropriate recommendation of fasciotomy, regardless of the ability of the examiner to correctly localize the compartment with the critical pressure elevation, the sensitivity was 54%, the specificity was 76%, the positive predictive value was 70%, and the negative predictive value was 63%.

Conclusions: Manual detection of compartment firmness associated with critical elevations in intracompartmental pressure is poor.

The diagnosis of compartment syndrome is based on the findings during serial physical examination, with direct measurements of intracompartmental pressure used as an adjunctive tool, particularly in obtunded patients[1-14]. The classic physical examination findings associated with established compartment syndrome are pain out of proportion to the injury, increased pressure or firmness of a compartment, paralysis, and paresthesias[12,15-17]. A highly sensitive test is preferred for the detection of compartment syndrome because of the substantial consequences of a missed diagnosis, including musculotendinous contractures, neurological deficits, amputation, organ failure resulting from rhabdomyolysis, and even death[11,18-20]. Unfortunately, the sensitivity of clinical findings (pain, pain with passive stretch, paresthesia, and paresis) for the diagnosis of compartment syndrome is low (13% to 19%)[6].

The ability to detect a critical elevation in intracompartmental pressure in an extremity prior to the onset of irreversible tissue ischemia is paramount for the timely diagnosis of compartment syndrome[1,18]. The critical pressure threshold varies from patient to patient and depends largely on the degree of limb perfusion, the patient's diastolic blood pressure, and the individual's tolerance of increased tissue pressure[1,19,21,22]. In animal models, the threshold at which cellular anoxia produces irreversible tissue damage occurs when in-

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tracompartmental pressures are elevated to within 20 mm Hg of the diastolic pressure[7,9,23]. In the clinical setting, the pressure threshold for decompressive fasciotomy was determined initially by Whitesides et al.[24] and revised by McQueen et al.[1,8] using the relationship between the intracompartmental pressure and the diastolic blood pressure. Their findings established the threshold to be a difference of ≤30 mm Hg between the diastolic pressure and the anterior leg compartment pressure (delta P [ΔP]). Intracompartmental pressure has been reported to be variable and is highest at the level of the fracture site and in the anterior and deep posterior compartments of the leg[1,3,8,10,22,25].

The clinical diagnosis of compartment syndrome is complicated in an obtunded patient. An examination finding that would not be expected to change on the basis of mental status is the firmness of the compartment to palpation. Direct palpation of the leg is performed as part of the routine clinical examination when there is a high index of suspicion for compartment syndrome. To our knowledge, no study has addressed the sensitivity of direct palpation of the leg for detection of elevated compartment pressure. Our study was designed to establish the sensitivity of manual palpation for detection of critical elevations in isolated intracompartmental pressures in the leg.

Materials and Methods

By adapting animal and cadaver models produced by Moed and Thorderson and Teng et al., we created a cadaver model system capable of generating sustained and reproducible elevations in intracompartmental pressures in the leg[23,26,27]. Five fresh, never-frozen cadavers were screened for evidence of previous surgery or injury to the lower extremities. Of these five cadavers, one was excluded from the study because radiographs demonstrated percutaneously placed hardware and a healed fracture in the distal part of the tibia. Four cadavers (eight legs) were used in the final protocol. The average age at the time of death was 74.5 years (range, sixty-five to eighty-seven years). Three of the donors were male, and one was female.

An uninterrupted fluid column was generated for each of the four leg compartments. Four 14-gauge angiocatheters were connected to intravenous tubing with Luer locks. These four tubing assemblies were connected to 1-L bags of normal saline solution and then inserted and secured by suturing into the anterior, lateral, superficial posterior, and deep posterior compartments of one cadaver leg. Different intracompartmental pressures were created by varying the fluid-column height (Fig. 1). An isolated intracompartmental pressure of 20, 40, 60, or 80 mm Hg was established in either the anterior or the deep posterior compartment[8,20], and the three remaining compartments remained at 20 mm Hg to act as internal controls. Twenty millimeters of mercury was chosen as the control pressure on the basis of the intracompartmental pressure measurements in uninjured human legs with the knee extended and the foot in a neutral position[25,27,28]. After raising the fluid column to the appropriate height to produce sustained pressure elevations in the control and experimental

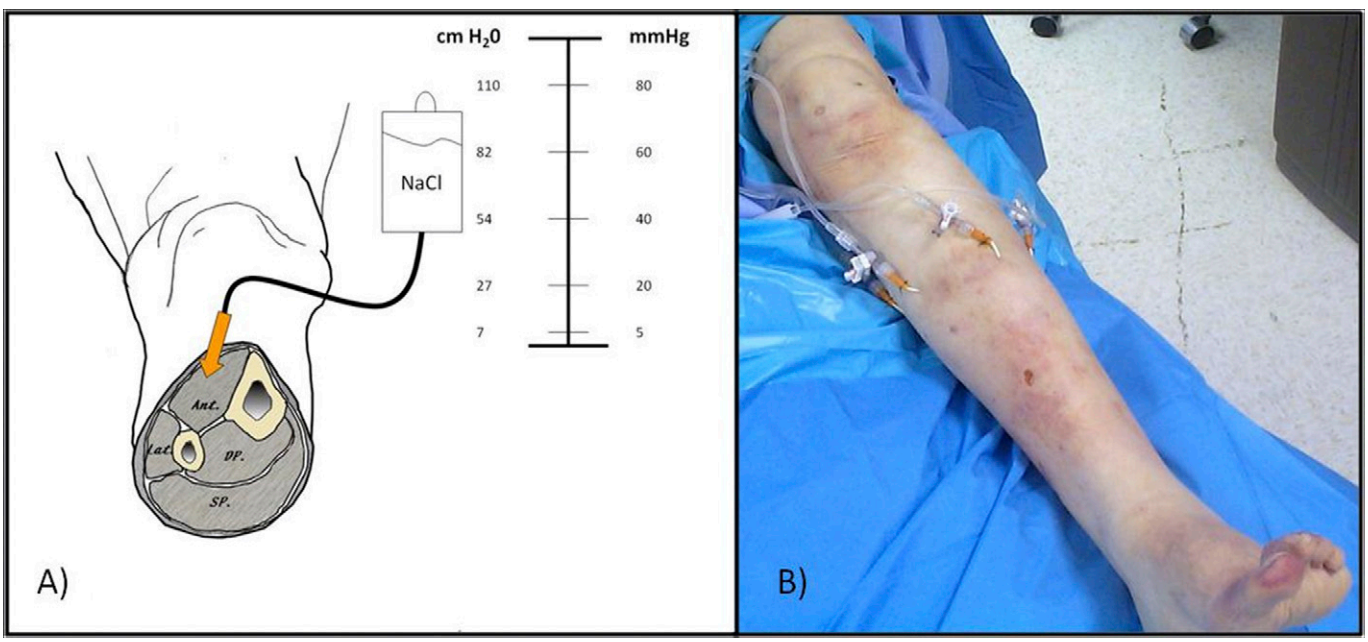

Fig. 1

Generation of sustained elevated compartment pressures. *A:* Changes in the height of the fluid column (1 L of normal saline solution) produce a steady-state pressure in the isolated compartment. The height (cm) producing the steady-state intracompartmental pressure (mm Hg) is shown. In our model system, a height of 54 cm produced an intracompartmental pressure of 40 mm Hg. All compartments other than the experimental one were maintained at a pressure of 20 mm Hg (a fluid column height of 30 cm)[23]. Ant., Lat., SP, and DP = anterior, lateral, superficial posterior, and deep posterior compartments, respectively. *B:* Photograph of a fresh cadaver leg (the test specimen) with angiocatheters inserted and secured into the four leg compartments. The correct intracompartmental placement of the catheters was confirmed for all specimens by dissection following completion of the study protocol.

TABLE I Sensitivity, Specificity, and Positive and Negative Predictive Values for Ability of Palpation to Detect and Localize Isolated Elevated Compartment Pressure

	Sensitivity *(%)*	Specificity *(%)*	Positive Predictive Value *(%)*	Negative Predictive Value *(%)*
Overall	24	55	19	63
Junior residents	26	57	21	64
Senior residents	23	69	27	64
Attending surgeons	22	36	11	56

compartments, we waited twenty minutes to allow for equilibration of the intracompartmental pressures. Direct intracompartmental pressure measurements (preliminary model validation with measurements at the proximal, middle, and distal compartmental levels) confirmed a consistent pressure throughout the entire compartment. In this study, intracompartmental pressures of 20 and 40 mm Hg were considered to not indicate a compartment syndrome, and pressures of 60 and 80 mm Hg were considered to be consistent with a compartment syndrome.

On nonconsecutive days, a new cadaver model was prepared and the pressure of the experimental compartment (anterior or deep posterior) was elevated. Orthopaedic surgery residents and faculty members at a level-I trauma center were invited to palpate the cadaver lower extremity, which was described to them as a "single-limb model of a patient who is obtunded, with a blood pressure of 120/80." The participants were blinded with regard to the height of the fluid column and the other participants' responses. They were asked three questions: (1) Is there a compartment syndrome? (2) In which compartment or compartments do you believe the pressure is elevated, if at all? (3) Describe your examination findings as soft, compressible, or firm. All compartment pressures were confirmed by direct pressure measurements with a calibrated and zeroed Stryker side-port needle manometer (Stryker, Kalamazoo, Michigan) before and after the participants' physical examinations. The accuracy and reproducibility of this measurement method has been validated[29]. After each day's testing, the placement of the angiocatheters into the correct compartment was confirmed by dissection and direct visualization. Of note, intracompartmental pressures of 60 and 80 mm Hg produced muscle bulging following fascial incision, which is consistent with intraoperative findings associated with a fascial release for an acute compartment syndrome in the leg. Additionally, elevated intracompartmental pressures did not alter adjacent compartment pressures; the control compartments remained at 20 mm Hg. Participants were individually escorted into the examination room and exited through a separate door to eliminate discussion of examination findings between participants and a possible bias.

Statistical Methods

A response was considered to be true-positive when the participant (1) detected an elevated intracompartmental pressure (60 or 80 mm Hg) and (2) correctly identified the compartment (anterior or deep posterior) with the elevated pressure. The response was defined as false-positive when the participant indicated that the pressure was elevated when in fact it was normal or that the increased pressure was located in a control compartment. A result was considered to be true-negative when the participant indicated "no compartment syndrome" in compartments with a pressure of 20 or 40 mm Hg, and it was considered to be false-negative when the volunteer answered "no compartment syndrome" with regard to compartments with a pressure of 60 or 80 mm Hg. Sensitivity, specificity, and the positive and negative predictive values were determined for the group as a whole and then for each subgroup: junior residents (in their first, second, or third postgraduate year), senior residents (in their fourth or fifth postgraduate year), and attending surgeons (board-certified/fellowship-trained).

Source of Funding

Our group received funding and two Stryker pressure manometers from the Stryker Foundation (Kalamazoo, Michigan). The research grant of $10,443 was used to purchase cadaveric specimens and materials needed to complete this research project.

Results

One hundred and thirty-six separate clinical examinations were performed over the defined range of leg intracompartmental pressures. Using the definition of a true-positive result as the correct detection of an elevated pressure and accurate localization to the experimental compartment, we found manual palpation to have a sensitivity of 24%, a specificity of 55%, a positive predictive

TABLE II Breakdown of True-Positive, False-Positive, True-Negative, and False-Negative Responses

	Condition Present +	Condition Present −
Localized by palpation		
+	10	43
−	31	52

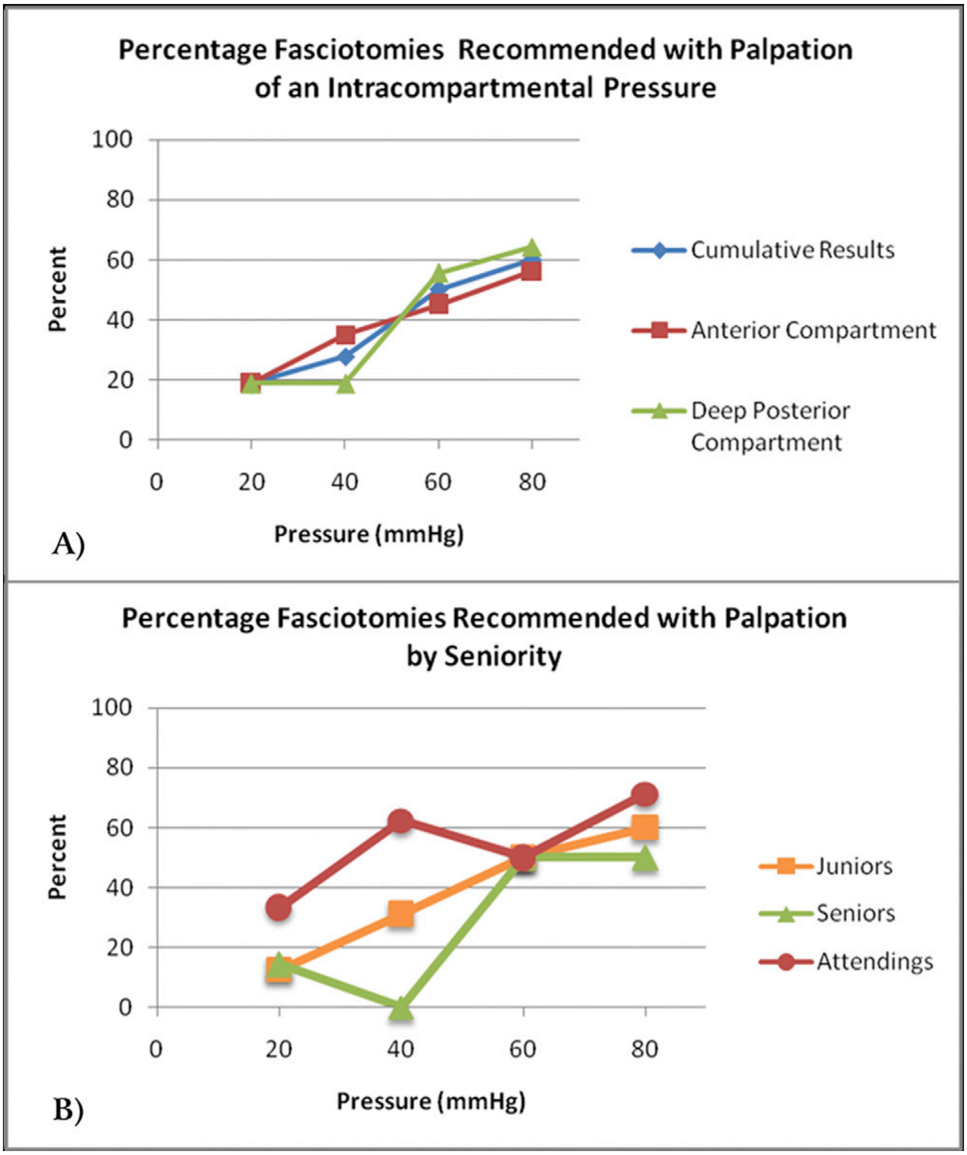

Fig. 2

Percentage of examinations resulting in a recommendation of fasciotomy, according to the pressure in either the anterior or the deep posterior compartment (A) and according to the seniority of the participant (B). The values in *B* are an average of the responses based on the examinations of the anterior and deep posterior compartments.

value of 19%, and a negative predictive value of 63% (Tables I and II). There were no significant differences based on surgeon experience. Sixty-three examinations were performed by eight junior residents, and the sensitivity of those examinations was 26%, the specificity was 57%, and the positive and negative predictive values were 21% and 64%, respectively. Thirty-nine examinations were performed by six senior residents: the sensitivity was 23%, the specificity was 69%, the positive predictive value was 27%, and the negative predictive value was 64%. Thirty-four examinations were performed by five attending surgeons: the sensitivity was 22%, the specificity was 36%, the positive predictive value was 11%, and the negative predictive value was 56%.

It was possible for a participant to correctly identify a critical elevation of intracompartmental pressure (the presence of a compartment syndrome) but incorrectly localize this finding to a control compartment. This scenario would result in the recommendation for fascial release and therefore appropriate clinical management. When we changed the definition of a true-positive result by discounting the ability of the examiner to localize the pressure correctly and defined it only as the clinicians' correct decision to perform a fasciotomy because of an elevated compartment pressure, the overall sensitivity increased to 54%, the specificity increased to 76%, the positive predictive value increased to 70%, and the negative predictive value remained the same.

TABLE III Description of Firmness of Compartment

Pressure *(mm Hg)*	Soft *(%)*	Compressible *(%)*	Firm *(%)*
20	59	31	9
40	29	57	13
60	12	47	44
80	20	33	45

The frequency of the recommendation for fasciotomy increased with increasing intracompartmental pressures (Fig. 2). The frequency with which an anterior compartment fasciotomy was recommended was 19% of the participants when the pressure was 20 mm Hg, 35% when it was 40 mm Hg, 45% when it was 60 mm Hg, and 56% when it was 80 mm Hg. The frequency with which a fasciotomy in the deep posterior compartment was recommended was 19% when the pressure was 20 mm Hg, 19% when it was 40 mm Hg, 56% when it was 60 mm Hg, and 64% when it was 80 mm Hg. One group (the attending surgeons) recommended fasciotomy in 100% of the cases in which the pressure was 80 mm Hg in the deep posterior compartment.

The participants were also asked to qualify their clinical interpretation of firmness as soft, compressible, or firm (Table III). The participants described the compartment as soft in 59% of the cases in which the pressure was 20 mm Hg in either the anterior or the deep posterior compartment. They described the compartment as firm in only 45% of the cases in which the pressure was 80 mm Hg.

Discussion

Compartment firmness is a direct manifestation of increased intracompartmental pressure and it is the earliest and possibly only objective sign of early compartment syndrome[3]. Serial evaluation and physical examination is recommended when there is a high index of suspicion for compartment syndrome. During the examination, pain (including pain with passive stretch), pressure, paralysis, paresthesia, and pallor are assessed[12]. Ulmer reported that the sensitivity of clinical findings (pain, pain with passive stretch, paresthesia, and paresis) for the diagnosis of compartment syndrome is low, ranging from 13% to 19%[6]. Pain, paralysis, and paresthesias cannot be assessed in obtunded patients. One physical examination finding that would not be expected to change with alterations in mental status and that would be thought to be present prior to the onset of tissue ischemia is compartment firmness. As shown here, palpation of compartment firmness is not a sensitive and reliable method for the noninvasive diagnosis of compartment syndrome.

In the group as a whole, manual palpation had a sensitivity of 54% and a specificity of 76% with regard to its ability to correctly identify critical elevations in intracompartmental pressures in the anterior and deep posterior compartments of the leg. Critical data analysis demonstrated a diminished sensitivity, specificity, and positive predictive value if the participant had to correctly identify the compartment responsible for the increased compartment firmness (sensitivity, 24%; specificity, 55%; and positive predictive value, 19%). As a result of the anatomical location of the deep posterior compartment, we would have expected more difficulty in assessing critical elevations of intracompartmental pressure in that compartment, but the data did not support that conclusion. When the intracompartmental pressure was 80 mm Hg in the deep posterior leg compartment, fasciotomy was recommended 64% of the time, whereas it was recommended 56% of the time when the pressure was 80 mm Hg in the anterior leg compartment.

It is important to note that, as intracompartmental pressures increased, the frequency of the recommendation for fasciotomy also increased. Manual palpation alone produced a high rate of false-positive results, with the participants recommending fascial release in 19% of the cases in which the pressure was 20 mm Hg and in only 60% of the cases in which it was 80 mm Hg. This corresponds well with the 45% frequency with which the compartment was described as firm to palpation when the pressure was 80 mm Hg (Table III). We expected surgeon experience to be an important variable; however, no significant differences in sensitivity and specificity were noted among junior residents, senior residents, and attending surgeons.

One concern about the data presented here is our use of a cadaver model system. This system does not provide a perfusion pressure, which is important for the clinical diagnosis of delta P and of compartment syndrome. Our model system also could not simulate the muscle tone and activation in a living patient. However, this model system would be analogous to the intraoperative assessment of compartment firmness in the setting of pharmacologic skeletal relaxation. An additional limitation of this study were the ages at the time of death (mean, 74.5 years) of the donors of the cadaver specimens from our Human Gift Registry. Our specimens had a corresponding decrease in muscle mass with noted thinning of the soft tissues, which would be expected to result in variability when these data are extrapolated to a younger or more obese population. These age-related changes are beneficial in this model system and represent a positive bias for the detection of fascial firmness. A decrease in the volume of the soft tissue between the fascia and skin should theoretically improve the detection of fascial firmness accompanying changes in intracompartmental pressures. An additional theoretical advantage in the cadaver model system is nontraumatized subcutaneous tissues. Swelling and inflammation of the subcutaneous tissues would be present in compartment syndrome associated with skeletal trauma. This additional barrier to assessment of compartment firmness would be expected to potentially decrease the clinical sensitivity of manual palpation. Our study would therefore be expected to have a positive bias in favor of improving the sensitivity of manual palpation for detecting fascial firmness because of the nontraumatized tissues. Our results clearly showed that, even with these added benefits in the model system, manual palpation still had poor sensitivity for detecting compartment firmness associated with critical elevations in intracompartmental pressure.

Our selection of 20 mm Hg for the control intracompartmental pressure deserves discussion. Gershuni et al. found that pressures in the anterior and deep posterior compartments of the legs of normal volunteers who had the knee extended varied depending on the position of the foot[28]. They reported that, with full passive ankle dorsiflexion, the average pressures in the anterior and deep posterior compartments were 28 ± 5 mm Hg and 36 ± 4 mm Hg, respectively. Our cadaver specimens had full knee extension and a neutral foot position. A neutral foot position would be expected to decrease the baseline pressures in the anterior and deep posterior compartments compared with the pressures with full passive ankle dorsiflexion[28]. Direct intracompartmental pressure measurements in uninjured human legs with knee extension and neutral foot flexion have been reported[25,27,28]. Prayson et al. measured pressures within the anterior compartment in ten uninjured legs of patients with a contralateral leg fracture who were undergoing surgical repair. The pressures averaged 19.7 mm Hg (subset data analysis with raw data provided by M.J. Prayson)[25]. Twenty millimeters of mercury was therefore set as the normal baseline pressure for the three control compartments in each leg tested in our study protocol.

The most important determinant of poor outcome from acute compartment syndrome is a delay in diagnosis. Compartment firmness is a fundamental finding in all cases of compartment syndrome in alert and obtunded patients. Firmness, a direct manifestation of increased intracompartmental pressure, is the earliest, and may be the only, objective finding of early compartment syndrome[3]. Previous studies have highlighted the low sensitivity of noninvasive physical examination for establishing this diagnosis[6,15,30-32]. This study confirms that the sensitivity of manual palpation of compartmental firmness is poor for the detection of elevated intracompartmental pressures in the leg and should not be used in isolation. The most accurate readily available technique should be used to establish the diagnosis of compartment syndrome[29]. We have challenged the assertion that the diagnosis of acute compartment syndrome is primarily clinical, especially in obtunded patients. We conclude that one should consider a more reliable means of assessing intracompartmental pressure in patients for whom there is a high index of suspicion for compartment syndrome and in obtunded patients with limited physical examination findings. ■

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