Interobserver Variability in the Measurement of Lower Leg Compartment Pressures

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Objectives: To determine whether interobserver technical variations and errors in the measurement of compartment pressures may affect measurement accuracy.

Methods: Four above-knee cadaveric specimens were used to create a consistent model of lower leg compartment syndrome. Thirty-eight physicians examined the limbs and measured 4 compartment pressures using the Intra-Compartmental Pressure Monitor (Stryker Orthopaedics). They were observed for correct assembly and use of the monitor. Measurements obtained were compared with known pressures.

Results: Of the total number of compartment measurements, 31% were made using the correct technique, 39% were made with lesser errors in technique, and 30% were made with catastrophic errors. Only 60% of measurements made with the correct technique were within 5 mm Hg of the standard pressure. Accuracy dropped to 42% for measurements taken with small errors in technique and 22% when a catastrophic error was committed.

Conclusions: Variations in use of a commercially available pressure monitor exist, and errors are common. Proper use improved accuracy, but even with proper technique, 40% of the measurements were >5 mm Hg from the actual pressure. Based on our data, measurement accuracy with this device should be questioned and viewed within a range. Regular review and education of technique is strongly recommended.

Key Words: compartment syndrome, measurement, variability, interobserver, compartment monitor, accuracy, trauma

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INTRODUCTION

The diagnosis of an acute compartment syndrome remains a clinical challenge. Signs and symptoms may include pain out of proportion to the injury, pain with passive stretch of the muscles involved, paralysis of the same muscles, paresthesia in the distribution of the peripheral nerves involved, pallor of the skin, and firmness of the affected compartments.[1–3] The accuracy and reliability of these clinical findings have been shown to be poor.[4,5] Some patients with a confounding clinical examination, or those intubated, sedated, or otherwise unable to cooperate with a clinical examination, may require measurement of their compartment pressures to make an appropriate diagnosis.[6] Failure to make the diagnosis may lead to sequelae including contractures and functional loss, infection, renal failure, amputation, and rarely death.[7–10] As a result, compartment syndrome is one of the more litigious diagnoses in orthopaedic surgery.[1,11]

Although the importance of accurate and timely diagnosis of compartment syndrome is universally agreed upon, the method and indications for pressure measurement remain unclear and inconsistent.[1–3,6,12,13] Although McQueen et al advocate for continuous monitoring and have recently shown excellent sensitivity and specificity for detecting compartment syndrome after tibia fractures, there is little evidence that this is being done on a regular basis in North America.[10,14,15] Choices include the Whitesides needle manometer, use of a slit catheter or a wick catheter.[16,17] Although these yield accurate pressure measurements, there seems to be a reluctance to accept them for continuous monitoring. The STIC Monitor (Stryker Orthopaedics, Mahwah, NJ) is a portable monitor that uses a side port needle, a disposable syringe of saline flush, and a digital read out manometer to allow for simple measurement of compartment pressure. Its accuracy in measuring a column of tissue and saline in a pressurized column has been validated.[18,19] Using a column of tissue and saline under 40 mm Hg pressure, the STIC was found to have a confidence

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interval of ± 6.23 mm Hg.[18] In another study, the confidence interval was at least ± 5 mm Hg, with several large outliers.[19]

Although validated in a controlled setting and compared with other techniques, the STIC Monitor has not been tested for measurement consistency in a cadaveric clinical model. Our hypothesis is that variations and errors in the technique of compartment pressure measurement using this device will lead to inaccurate measurements with potentially clinically relevant ramifications. To investigate this hypothesis, we invited physicians across our level I trauma center to measure compartment pressures in a cadaveric lower leg compartment syndrome model.

MATERIALS AND METHODS

Four unembalmed, thawed, above-knee cadaveric specimens were used to create a compartment syndrome model in the lower leg. The specimens were 48, 48, 58, and 59 years old. The model has been previously described and validated.[5,20–24] Normal saline was infused into the limb from an intravenous bag through a 16-gauge angiocatheter inserted into each of 4 compartments of the lower leg. Pressure was controlled by adjusting the height of the intravenous bags. To avoid gradual loss of pressure due to diffusion of saline across compartments, as seen by Chan et al[21] (and observed in our internal pilot trial with varying intercompartmental pressures), the pressure in each of the 4 compartments was set to the same pressure (see **Figure**, **Supplemental Digital Content 1**, http://links.lww.com/BOT/A326, showing photo of setup). The anterior compartments were monitored with indwelling slit catheters (see **Figure**, **Supplemental Digital Content 2**, http://links.lww.com/BOT/A327, showing photo of indwelling slit catheter setup). Catheter placement was verified by dissection after completion of the study (see **Figure**, **Supplemental Digital Content 3**, http://links.lww.com/BOT/A328, showing intracompartmental catheters after dissection). Pressures were measured by the investigators, before and after each participant, using the STIC Monitor to maintain compartment pressure by adjusting the saline bags' height as needed (Table 1). These measurements were considered the true compartment pressure and averaged to define a standard pressure (SP).

Participants were recruited from the Departments of Orthopaedic Surgery, Emergency Medicine, and General Surgery at a University affiliated Level I Trauma Center. They included resident, fellow, and attending physicians. Each was told, "This is the leg of a 45-year-old patient in a motor vehicle crash who sustained a closed diaphyseal tibia fracture. The patient is intubated and sedated in the intensive care unit, and their diastolic blood pressure is 70 mm Hg." Each volunteer was asked to assess the compartments' firmness. Their level of suspicion was recorded. Participants were asked to estimate the number of times they had used the monitor to measure compartments and then instructed to "measure the compartment pressures in all 4 compartments of the leg: anterior, lateral, superficial posterior, and deep posterior" using the device. Two of the investigators functioned as technical observers.

Participants were graded as demonstrating proper technique, committing minor technical errors, or catastrophic technical errors for each compartment measured. Proper technique was defined by the manufacturer's instructions on the back of the STIC Monitor as follows: assembly of the parts of the monitor, flushing the air from the system, zeroing the monitor at the approximate angle of entry, placement into the correct leg compartment, and flushing the system using <0.3 mL of saline. Minor errors in technique included failure to maintain the angle of insertion after zeroing the monitor, failure to use the proper amount of saline for flushing, and inconsistent zeroing of the monitor between each measurement. Catastrophic errors in technique were defined as 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, or failure to insert the needle into the correct anatomic space. Pressure measurements were recorded. Each measurement was compared with the SP, and any deviation was recorded. We defined a significant deviation to be one that was >5 mm Hg (SP ± 5), similar to Collinge and Kuper.[25]

All data were collected (see **Datasheet**, **Supplemental Digital Content 4**, http://links.lww.com/BOT/A329, showing data collected on each participant) and entered into an Excel 2002 spreadsheet (Microsoft Corporation, Redmond, WA). All analyses were performed using IBM SPSS v. 17.0 (IBM Corporation, Armonk, NY). Analyses were performed by participant (n = 38) or by individual compartment pressure measurement (n = 152). Graphic analysis was obtained using a scatter plot of all measurements relative to the SP. Chi-square was calculated for all nonparametric comparisons. The Kruskal–Wallis test was used to assess the relationship of reading the instructions, experience in using the monitor, and type of training with the technique. Post hoc testing was performed using the Mann–Whitney *U* test.

TABLE 1. Serial Control Measurements' Mean Values and SD (mm Hg) Demonstrating Consistency of the Model

	Anterior Compartment	Lateral Compartment	Superficial Posterior Compartment	Deep Posterior Compartment
Limb 1	45.8 ± 4.0	47.3 ± 2.3	46.8 ± 1.3	47.8 ± 2.2
Limb 2	48.8 ± 3.0	45.8 ± 5.9	46.5 ± 3.9	46.5 ± 4.4
Limb 3	45.2 ± 1.8	44.0 ± 2.7	42.6 ± 2.1	43.6 ± 1.5
Limb 4	50.0 ± 1.6	53.5 ± 3.8	43.1 ± 3.7	50.1 ± 1.1
Overall	47.5 ± 2.3	47.7 ± 4.1	44.8 ± 2.2	47.0 ± 2.7

RESULTS

There were 38 participants, of whom 27 (71%) were orthopaedists (12 residents, 6 fellows, and 9 attendings). The remaining 11 participants included 7 general surgery residents, 1 general surgery fellow, and 3 emergency medicine attending physicians. After physical examination alone, 18 (47%) were concerned about compartment syndrome based on the firmness of the limb to palpation. The instructions for use of the STIC Monitor were only read by 39% of the subjects. Although 83% (10/12) of nonorthopaedic physicians referred to the instructions, only 18.5% of the orthopaedists did and this was limited to 5 of 12 residents.

There were a total of 152 individual compartment measurements (Fig. 1). Catastrophic errors were committed in 30% (45), including failure to set up the monitor correctly by not flushing the air from the system, zeroing the monitor only after needle insertion, or failing to zero the monitor at any time. Anatomic errors included measurement of the anterior compartment medial to the tibia and failure to penetrate the fascia with the needle. Catastrophic errors were committed by all levels of training in this study: emergency department attendings, general surgery residents and fellows, and orthopaedic residents, trauma fellows, and trauma attendings. Of the 5 anatomic errors, 4 were committed by nonorthopaedists. Lesser errors or variations in technique were committed in 40% (60). These involved failure to zero the monitor between compartment measurements and variations in flushing. Flushing errors ranged from failure to flush after initial setup, to inconsistent flushing in each compartment, and to use of too much saline. We considered it a variation in technique to measure the deep posterior compartment from the lateral side as we were concerned whether the needle was long enough to reach the deep compartment from the lateral side. Another variation occurred when the needle was passed directly from the superficial posterior compartment into the deep posterior compartment without removal to measure both compartments. Although the possibility exists that accurate measurements may be made with this technique, there is also the chance that a change in direction and position without rezeroing the monitor first may lead to an inaccurate reading.

Correct measurements, as defined by the instructions on the monitor, were performed in 31% (47). Only 6 of 38 subjects measured all 4 compartments using the correct technique. Of the 6 participants who measured all 4 of the leg compartments correctly, 3 were orthopaedic trauma attendings, 2 were orthopaedic residents, and 1 was an emergency department attending. Three had used the monitor only 1–3 times previously, only 1 had used it greater than 10 times, and only 2 read the instructions. Level of training, specialty, experience using the monitor, and reading the instructions, all failed to have a significant effect on the likelihood of a catastrophic error in technique or in the likelihood of accurate measurement (within 5 mm Hg of the SP). Accuracy of measurement (<5 mm Hg) was significantly improved by use of proper technique (Table 2). Despite this, only 60% of correct measurements, 42% of those with lesser errors, and 22% of those with catastrophic errors were <5 mm Hg of SP (Fig. 2).

The leg pressures for this study were consistently kept in the range of 47 mm Hg (Table 1). Given the clinical scenario of a patient with diastolic blood pressure of 70 mm Hg, delta P = 23 mm Hg (indication for fasciotomy).[3,12–14] However, 63 of 152 intracompartmental pressure measurements (41.4%), however, were <40 mm Hg, giving a delta P $>$ 30 mm Hg, which would lead to the incorrect decision not to perform a fasciotomy. In practice, the measurement of even a single compartment pressure with delta P $<$ 30 mm Hg typically triggers a decision to perform a fasciotomy. Therefore, a decision not to perform fasciotomies requires an error in measuring all 4 compartments. This occurred with 10.5% of the participants (4/38): 3 orthopaedic surgery residents, 2 of whom did not read the instructions, and 1 general surgery resident who did read the instructions.

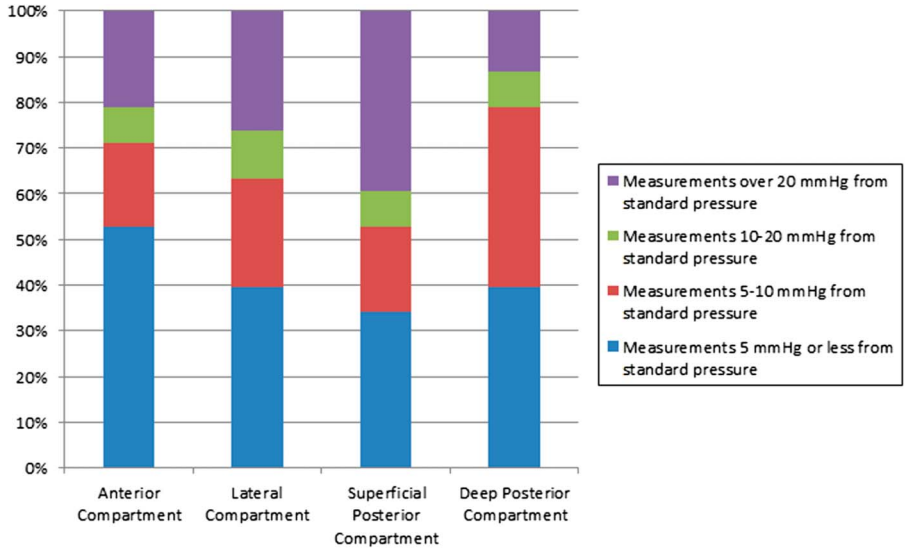

FIGURE 1. Percentage of measurements from the SP in each compartment. Note the wide variability of measurements and the number falling within ± 5 mm Hg and ± 10 mm Hg from the correct pressure.

TABLE 2. Mean Difference From Standard Pressure in 3 Groups Demonstrates Improved Accuracy With Proper Technique

	Mean and SD (mm Hg)
Proper technique (n = 47)	5.9 ± 7.1
Variant technique (n = 60)	10.8 ± 12.8
Catastrophic error (n = 45)	20.1 ± 14.0

Difference Between the catastrophic Error Group and the Other 2 Groups was Significant ($P < 0.001$).

DISCUSSION

Whitesides first described the use of needle manometer measurement of compartment pressure in the diagnosis of acute compartment syndrome.[16] Later techniques included the continuous saline infusion method of Matsen et al,[2] in which saline is infused and the resistance to infusion is used to measure the compartment pressure. Mubarak identified a compartment pressure of 30 mm Hg as being significantly resistant to infusion of fluid and recommended that this number be used as a threshold, above which acute compartment syndrome exists.[26] In 1996, McQueen and Court-Brown[14] demonstrated that compartment pressures well above 30 mm Hg can be tolerated without development of acute compartment syndrome, assuming that the blood pressure is sufficiently greater than the compartment pressure to provide continued perfusion of the tissues. She recommended that instead of an absolute threshold, there be a relative threshold for diagnosis, based on the difference between diastolic pressure and compartment pressure. Thus, the commonly accepted indication for fasciotomy is a delta P (diastolic pressure minus compartment pressure) of <30 mm Hg.[3,12–14]

Other variables may affect the reliability of compartment measurements. Use of end port or bevel-tipped needles has been found to overestimate the pressure, relative to the slit catheter and the side port needle by 2.9–18 mm Hg.[18,20,25,27] Hammerberg et al,[28] however, found good reliability of bevel-tipped needles as compared with slit catheters and side port needles. In vivo studies have documented several other variables within a limb that can affect the pressure. Nkele et al,[29] using a slit catheter, showed that limb and trunk position can affect measurement by up to 15 mm Hg. Heckman[30] showed that location of the measurement, relative to the site of a tibia fracture, can alter measurements. Heppenstall and Bernot demonstrated that ischemic tissue has reduced tolerance for elevated pressures.[31,32] Others have suggested that the tissue at the tip of the needle may affect results.[25,33]

Ulmer found that a clinical examination has poor sensitivity and a high negative predictive value, meaning that the physical examination tends to be better in ruling out compartment syndrome than it is in diagnosing it.[4] Shuler and Dietz[5] demonstrated poor interobserver reliability when using compartment firmness to palpation as a measure of elevated intracompartmental pressure in the leg. In their cadaveric study, 35% of participants recognized significant elevation when the anterior compartment was set to 40 mm Hg, but only 19% perceived the same level of increase in the deep posterior compartment. The diagnosis rates increased to 45% and 56%, respectively, when the pressures increased to 60 mm Hg. In our study, all compartments were kept at an equal pressure to prevent degradation due to diffusion between compartments. In keeping all 4 leg compartments at an average of 47 mm Hg, we found that only 47% of participants expressed concern for elevated pressures based solely on palpation.

Our hypothesis was that the myriad of variables when measuring compartment pressure would affect the accuracy of the results. We controlled the pressure of the limbs as closely as possible to 47 mm Hg in each compartment. Although our model of saline infusion has been validated and commonly used to create cadaveric compartment syndrome models, the ideal model has not been fully investigated to determine the effects of thawed versus fresh cadaver specimens, cadaveric age, and infusion of saline versus albumin to control compartment pressures.[5,20–24,34,35] All compartments were similarly elevated to prevent decay of pressure elevation by diffusion. This was based on our pilot trials, in which any attempt to preferentially raise pressure in a single compartment yielded diffusion over time and gradual loss of pressure. Although this may affect the ability of an examiner to detect

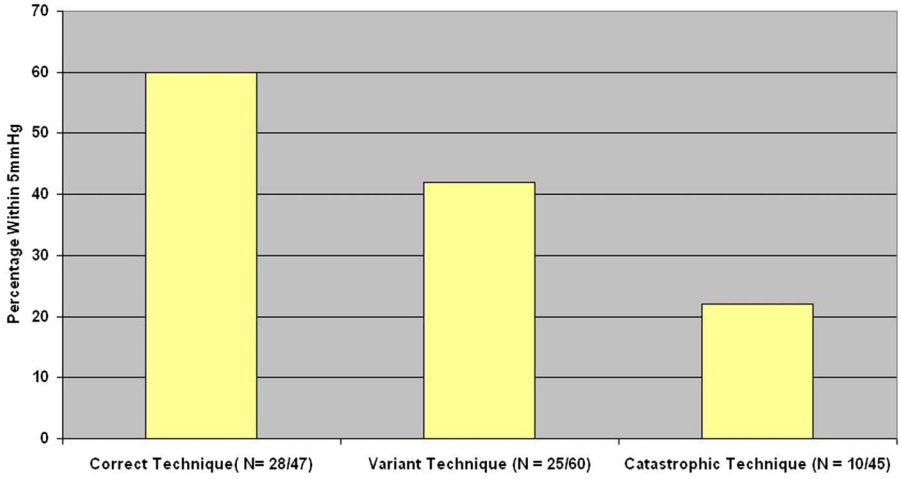

FIGURE 2. Percentage of measurements within 5 mm Hg of the SP for the 3 different technique groups. Accuracy improves as technique improves. Difference between the catastrophic error group and the other 2 groups was significant ($P < 0.05$). Difference between correct and variant technique groups trended toward significance ($P = 0.07$).

a tense compartment by palpation, in that the contrast is not evident when compared with an adjacent non-pressurized compartment, we chose this method to provide the most controlled pressure elevation possible. This lack of contrast versus other compartments also eliminated the differential as a means of validating which compartment the needle was placed. The determination that a compartment was incorrectly identified anatomically was only made when the error in needle insertion was obvious and egregious, such as measuring the anterior compartment pressure medial to the tibia. It is possible that the true rate of errors, based on the placement of the needle in the anatomically incorrect place, is different than what we identified. A further weakness of our study is that despite our maintenance of consistent cadaveric compartment pressures and definition of the examiner's measurements in relation to a consistently measured SP before and after their measurements, small variations in pressure could have occurred, which could affect any individual measurement from being in a defined threshold group, such as ± 5 mm Hg from the SP.

Interobserver accuracy of measurement was decreased because of variations and errors in technique. As indicated by our hypothesis, we anticipated the lesser variations in technique that we have defined above, but we did not anticipate the large number of catastrophic errors. Many errors were related to improper use of the equipment, despite the fact that instructions are clearly printed on the device itself. Although accuracy is improved when proper technique is used, the results still showed significant variability. Self-reported experience with the monitor, medical specialty, level of training, or even use of the printed instructions were not predictive of obtaining a reading within 5 mm Hg of the actual value. Even with correct technique, 40% of the measurements were off by at least 5 mm Hg. Similarly, the same factors were not predictive of the operator committing a catastrophic error in technique. Those who committed a catastrophic error were significantly less likely to obtain an accurate measurement.

If one assumes that when a single compartment pressure measurement meets the criteria for decompression, typically at a delta P < 30 mm Hg, then our model gave each participant 4 chances to reach a clinical decision to decompress. In reality, there may be only 1 or 2 compartments that meet the threshold, thus a diagnosis was more likely in our scenario. Despite this, 4 of 38 participants failed to obtain a single reading that was high enough to indicate fasciotomy. Regardless of how one defines successful use of a diagnostic tool, these represent failures of compartment pressure measurement.

Our study was designed to reflect real world situations and results with the STIC monitor. We intentionally avoided review or education of compartment pressure measurement techniques before the study. Even in highly controlled in vitro scenarios to validate the device, measurements often fell outside of a ± 5 mm Hg confidence interval, and larger variations were found when comparing the device with other measurement techniques.[18,19,25] Our findings corroborate those recently reported by Morris et al[36] that a 79% overall incidence of residents committing an error in compartment pressure measurement before an education session, a correlation of errors in technique with inaccurate measurements, and 68% of measurements not within 10 mm Hg of the correct pressure before their education session. In contrast to their study, we included 15 trauma fellows and attendings who also committed errors and obtained inaccurate measurements.

Our data support the notion that measurement of compartment pressure in clinical practice is not completely reliable, even when using a commercially available monitor, and despite correct technique. We recommend review of correct technique (Table 3) on a regular basis, such as every 2 years, with each participant observed for proper assembly and performance of compartment measurements into a suitable model (block of foam, fruit, or animal/cadaveric specimen). The decision to perform decompressive fasciotomies should be based on all available data understanding that the results obtained when measuring pressure may not be completely reliable.

TABLE 3. Correct Technique for Compartment Pressure Measurement

1. Assemble the monitor according to the directions on the back of the monitor and ensure all connections are tight
2. Flush saline through the line and needle so no air is present
3. Ensure battery is not corroded
4. Turn monitor on and ensure display shows a clear number
5. Hold the monitor perpendicular to the skin at the intended level and angle of insertion and zero the monitor
6. Insert the needle into the body
   - 1 cm lateral to the tibial crest for the anterior compartment
   - In-line with the axis of the fibular shaft for the lateral compartment
   - 0.5 cm posterior to the posteromedial border of the tibia aiming toward the posterior border of the fibula for the deep posterior compartment
   - Enter the superficial deep compartment from a midline posterior approach or from 2 cm posterior to the posteromedial border of the tibia with the needle parallel to the floor if the patient's toes are straight to the ceiling
7. Depth of needle insertion will vary based on the amount of subcutaneous fat and edema present but is generally 2–4 cm for the deep posterior compartment and 1–3 cm for the other compartments. You can usually feel when the needle penetrates the increased resistance of the fascia
8. Slowly inject less than 3/10 mL of saline into the compartment
9. Wait for the display to equilibrate before reading pressure
10. To confirm proper needle placement, palpation of the measured compartment should cause the reading to slightly increase
11. Remove needle from the body and move to the next compartment again zeroing the monitor at the level and angle of insertion before repeating steps 6–10

REFERENCES

1. Bourne R, Rorabeck C. Compartment syndromes of the lower leg. *Clin Orthop.* 1988;240:97–104.
2. Matsen F, Winquist R, Krugmire R. Diagnosis and management of compartmental syndromes. *J Bone Joint Surg Am.* 1980;62:186–191.
3. Shadgan B, Menon M, O'Brien P, et al. Diagnostic techniques in acute compartment syndrome of the leg. *J Orthop Trauma.* 2008;22:581–587.
4. Ulmer T. The clinical diagnosis of compartment syndrome of the lower leg: are clinical findings predictive of the disorder? *J Orthop Trauma.* 2002;16:572–577.
5. Shuler F, Dietz M. Physicians' ability to manually detect isolated elevations in leg intracompartmental pressure. *J Bone Joint Surg Am.* 2010;92: 361–366.
6. Olson S, Glasgow R. Acute compartment syndrome in lower extremity musculoskeletal trauma. *J Am Acad Orthop Surg.* 2005;13:436–444.
7. McQuillan W, Nolan B. Ischaemia complicating injury. *J Bone Joint Surg Br.* 1968;50:482–492.
8. Sheridan G, Matsen F. Fasciotomy in the treatment of the acute compartment syndrome. *J Bone Joint Surg Am.* 1976;58:112–115.
9. Thomas J. Nerve involvement in the ischaemic paralysis and contracture of Volkmann. *Ann Surg.* 1909;49:330–370.
10. McQueen M, Christie J, Court-Brown C. Acute compartment syndrome in tibial diaphyseal fractures. *J Bone Joint Surg Br.* 1996;78:95–98.
11. Bhattacharyya T, Vrahas M. The medical-legal aspects of compartment syndrome. *J Bone Joint Surg Am.* 2004;86:864–868.
12. Elliott K, Johnstone A. Review article: diagnosing acute compartment syndrome. *J Bone Joint Surg Br.* 2003;85:625–632.
13. White T, Howell G, Will E, et al. Elevated intramuscular compartment pressures do not influence outcome after tibial fracture. *J Trauma.* 2003; 55:1133–1138.
14. McQueen M, Court-Brown C. Compartment monitoring in tibial fractures. The pressure threshold for decompression. *J Bone Joint Surg Br.* 1996;78:99–104.
15. McQueen M, Duckworth A, Aitken S, et al. The estimated sensitivity and specificity of compartment pressure monitoring for acute compartment syndrome. *J Bone Joint Surg Am.* 2013;95:673–677.
16. Whitesides T, Haney T, Morimoto K, et al. Tissue pressure measurements as a determinant for the need of fasciotomy. *Clin Orthop Relat Res.* 1975;113:43–51.
17. McQueen M. How to monitor compartment pressures. *Tech Orthop.* 1996;11:99–101.
18. Boody A, Wongworawat M. Accuracy in the measurement of compartment pressures: a comparison of three commonly used devices. *J Bone Joint Surg Am.* 2005;87:2415–2422.
19. Uliasz A, Ishida J, Fleming J, et al. Comparing the methods of measuring compartment pressures in acute compartment syndrome. *Am J Emerg Med.* 2003;21:143–145.
20. Moed B, Thorderson P. Measurement of intracompartmental pressure: a comparison of the slit catheter, side-ported needle, and simple needle. *J Bone Joint Surg Am.* 1993;75:231–235.
21. Chan P, Steinberg D, Pepe M, et al. The significance of the three volar spaces in forearm compartment syndrome: a clinical and cadaveric correlation. *J Hand Surg Am.* 1998;23:1077–1081.
22. Cobb T, Cooney W, An K. Pressure dynamics of the carpal tunnel and flexor compartment of the forearm. *J Hand Surg Am.* 1995;20:193–198.
23. Havig M, Leversedge F, Seiler J. Forearm compartment pressures: an in vitro analysis of open and endoscopic assisted fasciotomy. *J Hand Surg Am.* 1999;24:1289–1297.
24. Teng A, Huang J, Wilber R, et al. Treatment of compartment syndrome: transverse fasciotomy as an adjunct to longitudinal dermatofasciotomy: an in vitro study. *J Orthop Trauma.* 2005;19:442–447.
25. Collinge C, Kuper M. Comparison of three methods for measuring intracompartmental pressure in injured limbs of trauma patients. *J Orthop Trauma.* 2010;24:364–368.
26. Mubarak S, Owen C, Hargens A, et al. Acute compartment syndromes: diagnosis and treatment with the aid of the wick catheter. *J Bone Joint Surg Am.* 1978;60:1091–1095.
27. Wilson S, Vrahas M, Berson L, et al. A simple method to measure compartment pressures using an intravenous catheter. *Orthopedics*. 1997;20:403–406.
28. Hammerberg E, Whitesides TE, Seiler JG. The reliability of measurement of tissue pressure in compartment syndrome. *J Orthop Trauma.* 2012;26:24–31.
29. Nkele C, Aindow J, Grant L. Study of pressure of the normal anterior tibial compartment in different age groups using the slit-catheter method. *J Bone Joint Surg Am.* 1988;70:98–101.
30. Heckman M, Whitesides TJ, Grewe S, et al. Compartment pressure in association with closed tibia fractures. The relationship between tissue pressure, compartment, and the distance from the site of the fracture. *J Bone Joint Surg Am.* 1994;76:1285–1292.
31. Heppenstall RB, Scott R, Sapega A, et al. A comparative study of the tolerance of skeletal muscle to ischemia. *J Bone Joint Surg Am.* 1986;68: 820–828.
32. Bernot M, Gupta R, Dobrasz J, et al. The effect of antecedent ischemia on the tolerance of skeletal muscle to increased interstitial pressure. *J Orthop Trauma.* 1996;10:555–559.
33. Nakhostine M, Styf J, van Leuven S, et al. Intramuscular pressure varies with depth. The tibialis anterior muscle studied in 12 volunteers. *Acta Orthop Scand.* 1993;64:377–381.
34. Odland R, Schmidt AH, Hunter B, et al. Use of tissue ultrafiltration for treatment of compartment syndrome. A pilot study using porcine hindlimbs. *J Orthop Trauma.* 2005;19:267–275.
35. Garr J, Gentilello L, Cole P, et al. Monitoring for compartmental syndrome using near-infrared spectroscopy: a noninvasvie, continuous, transcutaneous monitoring technique. *J Trauma.* 1999;46:613–618.
36. Morris MR, Harper BL, Hetzel S, et al. The effect of focused instruction on orthopaedic surgery residents' ability to objectively measure intracompartmental pressures in a compartment syndrome model. *J Bone Joint Surg Am.* 2014;96:e171. Available at: http://dx.doi.org/10.2106/JBJS.M.00582. Accessed December 5, 2014.