TOPICS IN TRAINING

The Effect of Focused Instruction on Orthopaedic Surgery Residents' Ability to Objectively Measure Intracompartmental Pressures in a Compartment Syndrome Model

Michael R. Morris, MD, Benjamin L. Harper, MD, Scott Hetzel, MS, Michael Shaheen, MD, Alan Davis, PhD, Blaise Nemeth, MD, and Matthew A. Halanski, MD

Investigation performed at Spectrum Health in conjunction with Grand Rapids Medical Education Partners, Grand Rapids, Michigan

Peer Review: This article was reviewed by the Editor-in-Chief and one Deputy Editor, and it underwent blinded review by two or more outside experts. The Deputy Editor reviewed each revision of the article, and it underwent a final review by the Editor-in-Chief prior to publication. Final corrections and clarifications occurred during one or more exchanges between the author(s) and copyeditors.

Acute compartment syndrome is a condition characterized by an increase in intracompartmental pressure within a closed fascial space, leading to muscle ischemia and tissue death if treatment is delayed¹⁻⁵. The medicolegal and economic impacts of compartment syndrome have been documented^{6,7}. Diagnosis of compartment syndrome can be difficult in children and in obtunded or unreliable patients^{8,9}. Use of an intracompartmental pressure measuring device, such as the Stryker Intra-Compartmental Pressure Monitor System (Stryker, Kalamazoo, Michigan), provides valuable information in such cases¹⁰⁻¹². This system has been shown to be highly accurate in the laboratory setting^{10,13}, but, from personal clinical experience, we hypothesized that the results might be inconsistent if residents used improper techniques.

Often, resident physicians are the first clinical staff to evaluate cases of suspected compartment syndrome. Prior to this study, residents at our institution used the Stryker device to document compartment pressures, but no formal assessment of their proficiency with the device existed. Thus, we set out to determine our residents' ability to use the device correctly (by measuring the number of technical errors they committed with

the device's use) and to document whether technical errors contributed to pressure measurement errors. Furthermore, we wanted to know whether a formal didactic presentation on the device's proper use would decrease technical errors and would improve accuracy of pressure measurements. Our hypothesis was that, prior to formal training, residents would demonstrate more technical errors using the device at baseline than after teaching and that the number of technical errors would correlate with pressure measurement errors. As the device requires rather simple technical skills, we hypothesized that improvements would be maintained at a later, nine-month, follow-up.

Materials and Methods

Study Design

There was a sample of convenience in the group of study subjects that included all orthopaedic surgery residents (postgraduate year 1 [PGY-1] to PGY-5) present for a single educational session at a single institution. This single session included baseline testing (pre-education), didactic education, and post-educational testing (post-education). A second testing session occurred nine months later. The primary outcome assessed was the number of technical errors (defined as deviations from the manufacturer's instructions on device use). The secondary outcome

Disclosure: None of the authors received payments or services, either directly or indirectly (i.e., via his or her institution), from a third party in support of any aspect of this work. None of the authors, or their institution(s), have had any financial relationship, in the thirty-six months prior to submission of this work, with any entity in the biomedical arena that could be perceived to influence or have the potential to influence what is written in this work. One or more of the authors has a patent or patents, planned, pending, or issued, that is broadly relevant to the work. In addition, one or more of the authors has had another relationship, or has engaged in another activity, that could be perceived to influence or have the potential to influence what is written in this work. The complete **Disclosures of Potential Conflicts of Interest** submitted by authors are always provided with the online version of the article.

Fig. 1

This schematic demonstrates the setup of the tested compartments. A 0.9% normal saline intravenous (IV) bag was placed in a pressure bag and connected to the compartment of interest using a large bore cannula. The compartment's pressure was continuously monitored using the Stryker Intra-Compartmental Pressure Monitor System (SICPMS) with the manufacturer's slit catheter option. Squeezing the manual pressure bulb on the pressure bag allowed the observers to maintain the pressure within the compartments at clinically relevant ranges during testing. The residents used identical SICPMSs with standard needles to measure the compartment's pressure.

assessed was the residents' ability to measure compartment pressures within 10 mm Hg of the actual real-time compartment pressures using a compartment syndrome model. These outcomes were assessed pre-education, post-education, and at the nine-month follow-up, using the handheld Stryker Intra-Compartmental Pressure Monitor System. Institutional review board exemption was granted for this quality improvement project.

Pre-Testing and Post-Testing Using the Porcine Model Pressure Elevation and Monitoring

To artificially elevate the pressure within a muscular compartment, a technique similar to that previously described in anesthetized canine¹² and human cadaveric limbs¹⁴ was utilized. The skin overlying the anterolateral compartments of three porcine thighs was marked using a marking pen, and a large bore intravenous needle was then inserted within the compartment and was connected to a 0.9% saline solution intravenous bag placed within a manual pressure bag. Using this technique, we were able to elevate the intracompartmental pressures within the desired compartment. Real-time pressures within the experimental compartment were determined by placing an indwelling slit catheter attached to a Stryker Intra-Compartmental Pressure Monitor System into this compartment. A schematic of the model is shown in Figure 1 and a photograph of the setup using one of the human cadaver legs is shown in Figure 2. This device has previously been proven to be extremely reliable in monitoring elevated compartment pressures¹⁰.

Using this system, we set out to mimic pressure readings that might be encountered clinically including high, medium, and low compartment pressures. The average compartment pressure (and standard deviation) in each limb was 44 ± 16 mm Hg for the high compartment pressure, 40 ± 5 mm Hg for the medium compartment pressure, and 17 ± 5 mm Hg for the low compartment pressure. Real-time compartment pressure measured using the slit catheter was recorded when each resident measured the pressure of that compartment using a second Stryker Intra-Compartmental Pressure Monitor System. Needle type, slit catheter or standard needle, was the only difference between the resident's Stryker Intra-Compartmental Pressure Monitor System and the system monitoring the real-time pressure within the compartment. Previous studies have demonstrated that differences in pressure measurements using these two different needle types with this device are negligible¹⁰. The slit catheter pressure was then defined as the true pressures within the compartment with which the residents' measurements were compared. This technique was used in all three

porcine limbs for the pre-education and post-education testing as well as at the nine-month evaluation substituting human cadaveric limbs for the porcine limbs.

Fig. 2

Photograph showing the setup for one of the cadaver limbs. Manual pressure infusion bags containing saline solution were used to elevate the compartments (A). A large bore cannula was placed into the compartment of interest (B). A Stryker monitor with the slit catheter was placed into the compartment of interest (C and C').

TABLE I Participant Experience with the Stryker Intra-Compartmental Pressure Monitor System

	Year in Training					Total
	PGY-1	PGY-2	PGY-3	PGY-4	PGY-5	
Total in program	6	5	5	5	5	26
Pre-education and post-education*	6	5	5	4	4†	24†
Prior training in Stryker system*	0	3	4	1	1	9
Person reported to have given prior training	NA‡	Junior resident, senior resident, staff	Three senior residents, staff	Senior resident	Staff	—
Stryker system use prior to education exercise§	0	4	11	11	17	43
Nine-month follow-up*	6	2	5	1	4	18
Used Stryker system since education exercise*	2	2	1	0	0	5
Uses since education exercise§	4	5	2	0	0	11

*The values are given as the number of residents. †One PGY-5 resident (B.L.H.) is a co-author of this study and was involved in the testing. ‡NA = not applicable. §The values are given as the self-reported number of uses.

Porcine Model Positioning

Three stations were set up to have the examiner approach the anterolateral compartment of the thigh from different angles to approximate checking the compartments of the leg. As the examiners did not expect the residents to know the location of the anterolateral compartment of the thigh in a pig, the skin overlying the compartment of interest had been clearly marked (as discussed above). The limbs were also positioned so as to encourage the examiner, mimicking approaches to compartments of the human lower limb, to approach from a lateral entry (horizontal or parallel to the floor) (Station #1) for the lateral compartment, a downward-directed angle (roughly perpendicular to the floor) (Station #2) for the anterior compartment, and an upward-directed angle (roughly perpendicular to the ceiling) (Station #3) for the posterior compartment. Thus, the residents were shown the location (from the skin marking) and the direction in which to stick the needle to place the needle correctly into the elevated porcine compartment.

Testing

Information was obtained on subject experience with the Stryker Intra-Compartmental Pressure Monitor System and the number of times of prior clinical use. For the first trial, the subjects were given an unassembled Stryker Intra-Compartmental Pressure Monitor System and were instructed to measure the intracompartmental pressure under the demarcated area with the Stryker Intra-Compartmental Pressure Monitor System. No instruction on assembly, use, or reading was provided, although the manufacturer's instructions on the back of the unit remained visible and were not hidden from the resident as this would represent what a resident might encounter clinically when asked to measure a compartment pressure. At each station, one observer (an orthopaedic resident [B.L.H.] and two volunteer medical students educated on the manufacturer's directions [M.S. and M.R.M.]) recorded the residents' ability to follow proper technique relative to the manufacturer's directions in the following five areas: (1) assembly, (2) purging of air prior to stick (at 45° and fluid was not allowed to run back into the transducer well), (3) zeroing just prior to stick and maintenance of entry angle throughout the process, (4) injection of <1/3 mL of fluid provided by the manufacturer in the syringe into the compartment to clear the needle, and (5) allowing appropriate time for the reading to stabilize. Thus, the technical errors for this study were defined as breaches in the manufacturer's instructions for these five aspects of the device's use. Baseline pressures obtained by the resident were recorded by each station's observer, as was the reading of the indwelling catheter pressure at that time. Each resident moved from station to station using the same Stryker Intra-Compartmental Pressure Monitor System, until completing all three stations. After all participants had finished the baseline (pre-education) testing at the three stations, an educational PowerPoint presentation (Microsoft, Redmond, Washington) was given that outlined the proper

assembly and use of the device. A revised version of this educational content for this publication can be found in the Appendix. Upon completion of the seminar, the subjects were asked to repeat the procedure using the porcine limbs and these data were recorded as the post-education measurements. Other than the depth of needle placement, subjects received no coaching during retesting.

Nine-Month Follow-up Using Human Cadaveric Limbs

Skill retention was assessed nine months later utilizing a human leg model to more accurately represent the clinical scenario and eliminate any confounding factors associated with the use of the porcine model. Follow-up testing provided an assessment of retention of proper technique and accuracy, as well as testing the residents' ability to place the needle correctly into the appropriate compartments in human anatomy. Two cadaveric lower limbs were prepared as previously described in the pig to maintain consistent compartment pressures within the lower limb. Two opposing compartments of the leg were maintained at a higher pressure: the anterior and superficial posterior compartments in one cadaver and the lateral and deep posterior compartments the other. Again, Stryker Intra-Compartmental Pressure Monitor Systems with indwelling slit catheters were utilized to determine the real-time pressures within the compartments. Residents were asked if they had used the Stryker Intra-Compartmental Pressure Monitor System since the previous trial and then measured all four compartments of both models while being evaluated for proper technique as before.

Statistical Analysis

Technical Error

Pre-education, immediate post-education, and nine-month follow-up testing were evaluated for the presence of technical errors over time with generalized estimating equations using a logit link function and resident as a random effect.

Measurement Error

Measurement error over the three time points was first assessed with repeated-measures analysis of variance (ANOVA) with time as a fixed effect and resident as the random effect. Then measurement error status (within 10 mm Hg of the correct pressure or not) over time was assessed with generalized estimating equations using a logit link function and resident as a random effect. We then used generalized estimating equation models to assess whether years of training or having training with the Stryker Intra-Compartmental Pressure Monitor System affected the relationship of measurement error status and time. We decided on this tolerance limit (10 mm Hg), as we felt pressure differences on the order of approximately 5 mm Hg may not clinically lead to differences in treatment; however, decisions in treatment

Fig. 3

A bar graph showing the percentage of participants who made possible technical errors or any error over time. PRE = pre-education, POST = post-education, and 9MONTH = nine-month follow-up.

might be altered as differences approached 10 mm Hg. Although this tolerance limit is arbitrary and may be different for different surgeons, we believe that 10 mm Hg, equating to an approximately 20% to 30% threshold measurement error, was a clinically relevant threshold to utilize in this study.

Effect of Technical Error on Measurement Error

Additional generalized estimating equation models were used to evaluate the effect of technical errors on measurement error status over the three time points. Technical errors within each specific step (assembly, purge, zero, inject, and stabilize) were assessed individually. We also looked to see if the number of technical errors (zero to five) and any technical errors (yes or no) played a role in the measurement error status over time.

Source of Funding

There was no external source of funding for this study. Stryker supplied the Stryker Intra-Compartmental Pressure Monitor Systems and donated cadavers.

Results

Participants

Twenty-four of the twenty-six total orthopaedic residents at our institution took part in the pre-education and post-education assessments. One PGY-4 resident was not present for the initial assessments and the other resident, a PGY-5 resident, was a co-author in this study (B.L.H.). Eighteen of the original twenty-four residents participated in the nine-month follow-up testing. Of the six residents not tested at nine months, three were PGY-2 residents and the other three were PGY-4 residents. The resident year in training, experience, and use of the Stryker Intra-Compartmental Pressure Monitor System can be seen in Table I.

Technical Error

The technical errors of assembly, purge, zeroing, injection, and stabilization were assessed comparing the resident's technique with the manufacturer recommendation. Purging was the most

common error observed. Errors were greatest pre-education, lowest immediately post-education, and in between at the nine-month follow-up (Fig. 3).

Table II shows the estimated odds ratios of each technical error by time points. With the exception of assembly, evaluations of technique showed a significant change after education in all steps of proper assembly and usage. In Figure 3, purge, zero, inject, stabilize, and if any error was made all show significant decreases in error rate from pre-education to post-education and pre-education to the nine-month follow-up ($p < 0.05$). Assembly showed a trend toward decrease from pre-education to post-education ($p = 0.092$), and a significant decrease from pre-education to the nine-month follow-up ($p = 0.028$). Retention of technical skill occurred at all steps at the nine-month follow-up.

Pressure Measurement Error

The actual mean pressure measurements were close to the actual compartment pressures over all time points and the mean measurement errors were fairly close to each other (Table III). However, the variance of the data was affected by the time intervals of pre-education, post-education, and nine-month follow-up (Fig. 4). There was a larger standard deviation for

Fig. 4

A line graph showing the estimation of density functions over time for the actual measurement error with boundary lines for ± 10 mm Hg. PRE = pre-education, POST = post-education, and 9MONTH = nine-month follow-up.

TABLE II Odds of Committing a Technical Error Over Time

Type of Error and Time	Odds Ratio*	Wald P Value
Assembly		
Pre-education	Reference	—
Post-education	0.22 (0.04 to 1.28)	0.092
At the nine-month follow-up	0.14 (0.03 to 0.81)	0.028
Purge		
Pre-education	Reference	—
Post-education	0.04 (0 to 0.27)	0.001
At the nine-month follow-up	0.28 (0.1 to 0.78)	0.014
Zero		
Pre-education	Reference	—
Post-education	0.04 (0.01 to 0.19)	<0.001
At the nine-month follow-up	0.35 (0.15 to 0.86)	0.021
Inject		
Pre-education	Reference	—
Post-education	0.05 (0.01 to 0.23)	<0.001
At the nine-month follow-up	0.25 (0.07 to 0.93)	0.038
Stabilize		
Pre-education	Reference	—
Post-education	0.14 (0.04 to 0.49)	0.002
At the nine-month follow-up	0.09 (0.01 to 0.78)	0.028

*The values are given as the odds ratio, with the 95% CI in parentheses.

the measurement error at pre-education (35 mm Hg) compared with post-education (11 mm Hg) and at the nine-month follow-up (9 mm Hg). Assessing measurement error by a tolerance limit of 10 mm Hg, we saw that there was significant improvement of measurements from pre-education to post-education ($p < 0.001$) and pre-education to the nine-month follow-up ($p < 0.001$). Table III summarizes the relationship between

measurement error and time. The odds of having a measurement error outside of the tolerance limit post-education was reduced by more than sixfold compared with the odds of having a measurement error outside of the tolerance limit at pre-education. This decrease was more than sevenfold when comparing pre-education measurements with those of the nine-month follow-up.

TABLE III Actual Measurement Error and Absolute Measurement Errors of >10 mm Hg Over Time

Type of Error	Time		
	Pre-Education	Post-Education	At the Nine-Month Follow-up
Actual difference			
Mean*	−1	1	−5
Estimate†	Reference	3 (−4 to 9)	−3 (−9 to 2)
P value	—	0.407	0.220
Absolute difference of >10 mm Hg			
Percentage‡	68.1%	25.0%	22.9%
Odds ratio§	Reference	0.16 (0.06 to 0.43)	0.14 (0.07 to 0.30)
Wald p value	—	<0.001	<0.001

*The value is the raw mean value. †The values are given as the estimate, derived from a repeated-measures ANOVA model, with the 95% CI in parentheses. ‡The value is the percentage of all measures with measurement error. §The value is given as the odds ratio, with the 95% CI in parentheses.

TABLE IV Effect of Years in Training or Prior Stryker Intra-Compartmental Pressure Monitor System Training on Measurement Error of Absolute Difference of >10 mm Hg at Each Time Point

Time and Variable	Odds Ratio*	Wald P Value
Pre-education		
Years of training	0.45 (0.31 to 0.66)	<0.001
Stryker Intra-Compartmental Pressure Monitor System training	1.87 (0.51 to 6.91)	0.349
Post-education		
Years of training	0.93 (0.62 to 1.41)	0.739
Stryker Intra-Compartmental Pressure Monitor System training	0.26 (0.05 to 1.22)	0.088
Follow-up		
Years of training	0.87 (0.53 to 1.44)	0.596
Stryker Intra-Compartmental Pressure Monitor System training	1.85 (0.53 to 6.43)	0.332

*The values are given as the odds ratio, with the 95% CI in parentheses.

Postgraduate years of training significantly affected measurement error pre-education ($p < 0.001$), but lost its effect post-education (Table IV). At the pre-education time point, each additional year in training decreased the residents' likelihood of making an error of >10 mm Hg nearly twofold. However, this significance was lost at both the post-education and the nine-month time points.

Effect of Technical Error on Measurement Error

The occurrence of technical errors affected measurement error. Table V demonstrates the odds ratio of performing a measurement error when technical errors occurred. The odds of making a measurement error significantly increased when committing technical errors of assembly ($p = 0.009$), zeroing ($p < 0.001$), or injection ($p = 0.004$). All of these errors increased the odds of an error of >10 mm Hg by about threefold. However, a stabilization

error only marginally increased the odds of making a measurement error ($p = 0.074$), and purge errors did not have a significant effect on measurement error ($p = 0.785$). The number of technical errors the resident made was marginally related to measurement error. For each additional technical error, the odds of the measurement error increased by 50% (odds ratio, 1.50 [95% confidence interval (95% CI), 1.00 to 2.22]; $p = 0.051$).

Discussion

Using this model to assess the residents at our single institution, we were successful in demonstrating that the number of technical errors committed by the residents diminished after focused instruction. Similarly, we have demonstrated that technical errors increase the likelihood of a measurement error. At baseline (pre-education), more senior residents demonstrated a lower likelihood of committing measurement errors. However, formal education decreased the measurement errors of the less experienced residents, which suggests that formal instruction appeared to level the playing field between residents at different levels of training. Conversely, measurement error over time was not significantly affected by whether the resident had reported receiving previous training in the Stryker Intra-Compartmental Pressure Monitor System prior to taking part in this study.

There were limitations to this study. First, a sample of convenience was utilized in this study, by only including trainees from a single training center. We attempted to limit this bias by including all available residents for participation. Whether these results can be extrapolated to trainees at other centers is unknown. One may argue that changing models added an unnecessary potential for the variability of our results. We acknowledge this potential weakness, but would argue that committing technical errors with the Stryker Intra-Compartmental Pressure Monitor System should be independent of the model, as these errors are dependent on the user and the device alone. Furthermore, the ability of the technical errors to influence measurement errors should be inherent in the device and independent of the model. The largest variability added by the change in model

TABLE V The Odds of Committing a Measurement Error Over Time When a Given Technical Error Is Performed

Technical Error	Odds Ratio*	Wald P Value
Assembly	3.58 (1.37 to 9.34)	0.009
Purge	1.16 (0.41 to 3.30)	0.785
Zero	2.99 (1.69 to 5.28)	<0.001
Inject	3.06 (1.44 to 6.50)	0.004
Stabilize	2.59 (0.91 to 7.36)	0.074
No. of errors†	1.50 (1.00 to 2.24)	0.051
Any error: Yes†	1.80 (0.71 to 4.59)	0.216

*The values are given as the odds ratios, with the 95% CI in parentheses. Odds ratios are estimated for each variable while controlling for time. No interaction terms were significant.
†Analysis was conducted on only the data for which all five error types were possible.

would be anatomic differences between the compartments and subcutaneous tissues between the porcine and human limbs. This might affect the residents' ability to accurately place the needle with the compartment of interest. Thus, one might argue that going from a less familiar model (pig) to a more familiar model (human leg) may have falsely biased our results to show improvement at nine months. However, we attempted to minimize the effect of the residents' unfamiliarity with the porcine anatomy by marking the skin directly overlying the compartment to be tested and by telling the residents in which direction to stick the needle to ensure that they would hit the correct compartment. As the location and direction of the compartment were given to the residents, we believe that the human model, although more familiar, was actually a more difficult testing situation as none of the compartments were marked on the human model, forcing the residents to assimilate their Stryker Intra-Compartmental Pressure Monitor System and anatomic knowledge to properly measure the compartments. An unanticipated potential confounding factor realized after the pre-education and post-education testing was that the observers unfortunately coached correct needle placement, likely in terms of the needle's depth in the post-education group. If placement of the needle was outside the elevated compartment because of the use of porcine model initially and if the coaching was responsible for the decrease in measurement error post-education, one would expect the pre-education errors to be significantly lower than the actual compartment pressures (due to the fact that the needle did not enter the elevated compartment) and the post-education errors to be more evenly distributed (higher or lower than the actual pressure). The proportion of errors (outside the 10-mm Hg window) was equally distributed both pre-education and post-education. Of the forty-nine errors, thirty-four (69.4%) were made on the negative side of 10 mm Hg at post-education. These were not significantly different. Perhaps coaching proper needle depth demonstrates another potential area on which the supervising surgeons can focus to help residents become proficient in this technique. Proper needle placement might also be studied in the future to further improve pressure measurements.

To minimize the fluctuation of pressures experienced in our high pressure model, plasma or a balloon, rather than saline solution, could have been used to maintain elevated compartment pressures¹⁵. Although not tested in this study, a technical tip that could have been used to ensure that the needle was inserted into the correct compartment would have been to manually squeeze or depress the compartment of interest while measuring the pressure; this should have caused the readings to elevate if needle placement was correct. Similarly, in the clinical situation, a cooperative patient could be asked to contract muscles within the compartment being tested and an increase in pressure would be noted. Finally, all clinicians should realize that these devices may require scheduled calibration to ensure they are accurate.

This study demonstrates the value in formally educating residents with the use of the compartment pressure monitor used at their institution, as many (>50%) of the residents at our institution did not measure the elevated compartments

within 10 mm Hg of the actual pressure at the start of this study (Table III). With one didactic session and the two testing periods, technical improvements were maintained within a reasonable degree nine months later. Furthermore, almost 20% of resident measurements continued to make measurements of >10 mm Hg off the actual slit catheter measurements after instruction in the porcine and human models. As the Stryker Intra-Compartmental Pressure Monitor Systems have proven to be extremely accurate and reliable in the controlled laboratory setting¹⁰, this error after training may be the limits of the device's clinical reliability in the hands of the residents or may represent local differences in compartment pressures between the site of the slit catheter placement and testing area, although the window of 10 mm Hg should minimize the potential confounding effect of a pressure gradient within the compartment. In either case, this highlights the potential pitfalls of using a single measurement to guide clinical decisions. Averaging multiple measurements may have improved accuracy, as the mean measurements among all of the participants were very close to the actual compartment pressure (Table II); however, this issue was not formally investigated, but it might be a direction of future study.

The timing and results of this study are fortuitous, as a recent report by the Council of Orthopaedic Residency Directors (CORD) outlined the upcoming changes to all resident training programs¹⁶. As of the 2013 to 2014 academic year, each residency is mandated by the Orthopaedic Residency Review Committee of the Accreditation Council of Graduate Medical Education (ACGME) and the American Board of Orthopaedic Surgery (ABOS) to institute a Surgical Skill Training Curriculum for PGY-1 residents. The requirements of this curriculum are¹⁶: "a formal curriculum, goals and objectives, assessment metrics, instruction in basic operative skills and basic skills required to manage injured patients, and space." The current study would support efforts by the ACGME and ABOS to require residents to demonstrate proficiency in compartment syndrome monitoring by providing baseline data documenting the need for formal training (our baseline data), the immediate and short-term results of education, and the possible assessment metrics to be used for documenting proficiency in this procedure. Although establishing the fidelity of these models was not the focus of this study, we would suggest that the model(s) used in this study might provide a means by which other institutions could fulfill the new requirements at a relatively low cost.

In conclusion, to our knowledge, this study is the first to demonstrate the number of technical and measurement errors made by residents when evaluating compartment pressures using a very common compartment pressure measuring device. Furthermore, this study demonstrates the sustained improvement in technique and measurement accuracy before and after formal education. Importantly, this study is also the first to demonstrate that technical errors lead to increased measurement errors when evaluating compartment pressures using the Stryker Intra-Compartmental Pressure Monitor System. We believe that this study supports the ACGME and ABOS new requirements to objectively measure proficiency in compartment pressures monitoring.

Appendix

A slide show of compartment syndrome and the Stryker Intra-Compartmental Pressure Monitor System is available with the online version of this article as a data supplement at jbjs.org. ■

Michael R. Morris, MD
Benjamin L. Harper, MD
Michael Shaheen, MD

Alan Davis, PhD
Spectrum Health,
Grand Rapids Medical Education Partners,
100 Michigan Street,
Grand Rapids, MI 49503

Scott Hetzel, MS
Blaise Nemeth, MD
Matthew A. Halanski, MD
University of Wisconsin-Madison,
Department of Orthopedics & Rehabilitation,
1685 Highland Avenue, 6273 MFCB,
Madison, WI 53705.
E-mail address for M.A. Halanski: Halanski@ortho.wisc.edu

References

- Bourne RB, Rorabeck CH. Compartment syndromes of the lower leg. *Clin Orthop Relat Res*. 1989 Mar;(240):97-104.
- Gelberman RH, Garfin SR, Hergenroeder PT, Mubarak SJ, Menon J. Compartment syndromes of the forearm: diagnosis and treatment. *Clin Orthop Relat Res*. 1981 Nov-Dec;(161):252-61.
- Matsen FA 3rd. Compartmental syndrome. An unified concept. *Clin Orthop Relat Res*. 1975 Nov-Dec;(113):8-14.
- Matsen FA 3rd, Winquist RA, Krugmire RB Jr. Diagnosis and management of compartmental syndromes. *J Bone Joint Surg Am*. 1980 Mar;62(2):286-91.
- Rorabeck CH. The treatment of compartment syndromes of the leg. *J Bone Joint Surg Br*. 1984 Jan;66(1):93-7.
- Bhattacharyya T, Vrahas MS. The medical-legal aspects of compartment syndrome. *J Bone Joint Surg Am*. 2004 Apr;86(4):864-8.
- Templeman D, Varecka T, Schmidt R. economic costs of missed compartment syndromes. *J Orthop Trauma*. 1993;7:180.
- Whitesides TE, Haney TC, Morimoto K, Harada H. Tissue pressure measurements as a determinant for the need of fasciotomy. *Clin Orthop Relat Res*. 1975 Nov-Dec;(113):43-51.
- Willis RB, Rorabeck CH. Treatment of compartment syndrome in children. *Orthop Clin North Am*. 1990 Apr;21(2):401-12.
- Boody AR, Wongworawat MD. Accuracy in the measurement of compartment pressures: a comparison of three commonly used devices. *J Bone Joint Surg Am*. 2005 Nov;87(11):2415-22.
- Collinge C, Kuper M. Comparison of three methods for measuring intracompartmental pressure in injured limbs of trauma patients. *J Orthop Trauma*. 2010 Jun;24(6):364-8.
- Moed BR, Thorderson PK. Measurement of intracompartmental pressure: a comparison of the slit catheter, side-ported needle, and simple needle. *J Bone Joint Surg Am*. 1993 Feb;75(2):231-5.
- McDermott AG, Marble AE, Yabsley RH. Monitoring acute compartment pressures with the S.T.I.C. catheter. *Clin Orthop Relat Res*. 1984 Nov;(190):192-8.
- Shuler FD, Dietz MJ. Physicians' ability to manually detect isolated elevations in leg intracompartmental pressure. *J Bone Joint Surg Am*. 2010 Feb;92(2):361-7.
- Kalns J, Cox J, Baskin J, Santos A, Odland R, Fecura S Jr. Threshold model for extremity compartment syndrome in swine. *J Surg Res*. 2011 May 1;167(1):e13-9. Epub 2011 Jan 31.
- American Orthopaedic Association. Marsh JL, Pedowitz R. A surgical skills training curriculum for orthopaedic PGY-1. AOA CORD Report. 2013 Feb.
- Seddon HJ. Volkmann's ischaemia in the lower limb. *J Bone Joint Surg Br*. 1966 Nov;48(4):627-36.
- Nolan B, McQuillan WM. Acute traumatic limb ischaemia. *Br J Surg*. 1965 Aug;52:559-65.
- Blick SS, Brumback RJ, Poka A, Burgess AR, Ebraheim NA. Compartment syndrome in open tibial fractures. *J Bone Joint Surg Am*. 1986 Dec;68(9):1348-53.
- Mubarak SJ, Owen CA, Hargens AR, Garetto LP, Akeson WH. Acute compartment syndromes: diagnosis and treatment with the aid of the wick catheter. *J Bone Joint Surg Am*. 1978 Dec;60(8):1091-5.
- McQueen MM, Court-Brown CM. Compartment monitoring in tibial fractures. The pressure threshold for decompression. *J Bone Joint Surg Br*. 1996 Jan;78(1):99-104.
- Heckman MM, Whitesides TE Jr, Grewe SR, Judd RL, Miller M, Lawrence JH 3rd. Histologic determination of the ischemic threshold of muscle in the canine compartment syndrome model. *J Orthop Trauma*. 1993;7(3):199-210.
- Heppenstall RB, Sapega AA, Scott R, Shenton D, Park YS, Maris J, Chance B. The compartment syndrome. An experimental and clinical study of muscular energy metabolism using phosphorus nuclear magnetic resonance spectroscopy. *Clin Orthop*. 1988 Jan;(226):138-55.
- Matava MJ, Whitesides TE Jr, Seiler JG 3rd, Hewan-Lowe K, Hutton WC. Determination of the compartment pressure threshold of muscle ischemia in a canine model. *J Trauma*. 1994 Jul;37(1):50-8.
- Hargens AR, Akeson WH, Mubarak SJ, Owen CA, Gershuni DH, Garfin SR, Lieber RL, Danzig LA, Botte MJ, Gelberman RH. Kappa Delta Award paper. Tissue fluid pressures: from basic research tools to clinical applications. *J Orthop Res*. 1989;7(6):902-9.
- Halpern AA, Nagel DA. Compartment syndromes of the forearm: early recognition using tissue pressure measurements. *J Hand Surg Am*. 1979 May;4(3):258-63.
- Halpern AA, Nagel DA. Anterior compartment pressures in patients with tibial fractures. *J Trauma*. 1980 Sep;20(9):786-90.
- Bernot M, Gupta R, Dobrasz J, Chance B, Heppenstall RB, Sapega A. The effect of antecedent ischemia on the tolerance of skeletal muscle to increased interstitial pressure. *J Orthop Trauma*. 1996;10(8):555-9.