Accuracy in the Measurement of Compartment Pressures: A Comparison of Three Commonly Used Devices

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Background: In situations in which accurate physical diagnosis is inconclusive, an objective method for measuring compartment pressure can aid in the diagnosis of compartment syndrome. Previous studies have compared measurement devices with each other but not with an accurately determined gold standard. The purpose of the present study was to devise a reproducible in vitro model of compartment pressure and to compare commonly used measurement devices in order to determine their accuracy.

Methods: With a graduated cylinder being used to generate a known pressure, freshly harvested ovine muscle was placed into a chamber for testing. The cylinder was incrementally filled with saline solution (in fifty-five steps), and measurements of tissue pressure were obtained with use of the Stryker Intracompartmental Pressure Monitor System, an arterial line manometer, and the Whitesides apparatus. Each device was tested with a straight needle, a side-port needle, and a slit catheter, for a total of nine setups in all. Five trials were done with each setup. Control pressures were calculated on the basis of the height of the saline solution column (test range, 0.13 to 10.80 kPa). Multiple regression analysis was used to compare measured tissue pressures with calculated control pressures.

Results: Most methods demonstrated excellent correlation ($R^2 > 0.95$) between calculated and measured pressures. The arterial line manometer with the slit catheter showed the best correlation ($R^2 = 0.9978$), and the Whitesides apparatus with the side-port needle showed the worst ($R^2 = 0.9115$). Furthermore, the Stryker system with the side-port needle demonstrated the least constant bias (+0.06 kPa). Straight needles tended to overestimate pressure. Two of the three needle configurations involving the Whitesides apparatus overestimated pressure. The data for the Whitesides methods had the highest standard errors, showing clinically unacceptable scatter.

Conclusion: Side-port needles and slit catheters are more accurate than straight needles are. The arterial line manometer is the most accurate device. The Stryker device is also very accurate. The Whitesides manometer apparatus lacks the precision needed for clinical use.

Clinical Relevance: When physical examination findings are inconclusive, accurate measurement of compartment pressures can aid in timely management and can minimize patient morbidity. Measurement should be done with use of the most accurate technique available.

Compartment syndrome is a serious, potentially limb-threatening condition for which a timely, accurate diagnosis is essential for an optimal outcome[1-3]. The natural history of untreated compartment syndrome has been well delineated[1,4,5]. The diagnosis is primarily based on physical examination signs and patient symptoms. Unfortunately, an adequate examination is sometimes inconclusive or impossible to perform, especially when the patient is obtunded or has sustained polytrauma. In these cases, an objective method for the measurement of intracompartmental pressure can aid in timely diagnosis[6-8]. Several methods of measuring tissue pressure have been proposed in an attempt to supplement the physical examination findings and to aid in the timely diagnosis of compartment syndrome[9-15].

Accuracy and reproducibility are the main concerns regarding devices that are used to measure intracompartmental pressure. Wide pressure variations have been observed even when only one device has been used for the evaluation of pa-

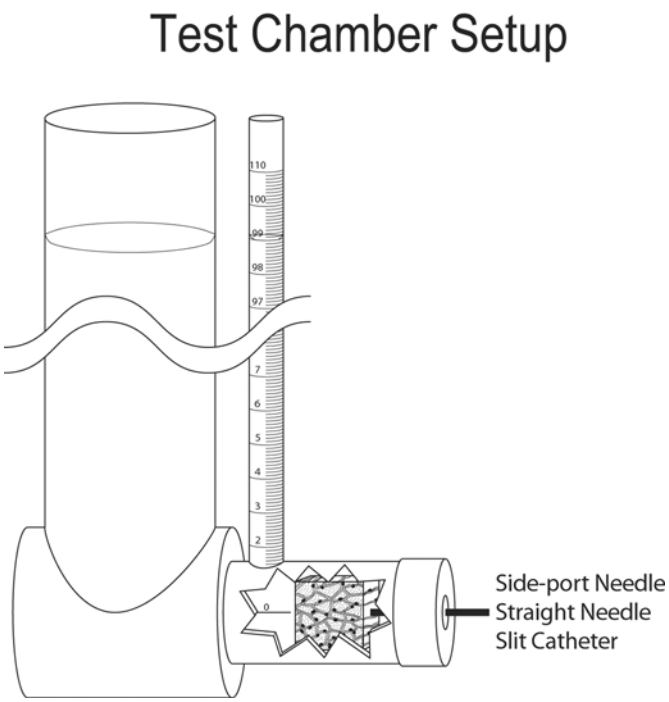

Fig. 1

The test chamber consisted of a large column for saline solution with another clear, graduated column for reading the fluid meniscus.

tients who were not suspected of having a compartment syndrome[16-19]. As none of these devices have been tested against a known pressure in a standard model involving muscle tissue, it is unclear whether these variations are due to inaccuracy of the device, measurement error, or natural variations in compartment pressure. Although numerous studies have compared these devices with each other[10-12,14,15,19], there is a lack of compelling evidence that they are accurate when compared with a known pressure. In two recent studies, pressures that had been determined with use of a measurement device were compared with a known pressure, but neither of those studies involved the use of muscle tissue in the control standard[13,16].

We fashioned a model involving muscle tissue to reproducibly generate a known pressure. With use of this model, we sought to determine which of three commonly used devices (if any) was most accurate for the measurement of intracompartmental pressure.

Materials and Methods

A graduated cylinder with a side port was constructed (Fig. 1). The graduated portion of the apparatus was clear, allowing visualization of the fluid meniscus against the graduated markings to determine fluid level.

After executive approval had been obtained from the Animal Use and Care Committee at our institution, fresh ovine muscle tissue was harvested at the time that the animals were killed. Gluteal muscle was harvested sharply and was cut into 2-cm cubes, each weighing 9 g. The epimysium was not harvested. The muscle tissue was placed into the side port at the bottom of the cylinder for testing. The side port measured 3.5 cm in diameter. Thus, the cube of muscle did not impinge on the walls of the side port. Needles and catheters corresponding with each of three devices were introduced into the center of the muscle; the devices included an arterial line transducer connected to a digital manometer, a handheld compartment monitor (Stryker Intracompartmental Pressure Monitor System; Stryker, Kalamazoo, Michigan), and a Whitesides apparatus[9]. Each device was tested with use of an 18-gauge straight needle, an 18-gauge side-port needle, and a slit catheter (Fig. 2). Thus, testing involved a total of nine setups, including the Stryker device with the side-port needle, the straight needle, and the slit catheter; the arterial line manometer with the side-port needle, the straight needle, and the slit catheter; and the Whitesides apparatus with the side-port needle, the straight needle, and the slit catheter. Normal saline solution at 37°C was used to fill the cylinder incrementally. All nine modalities were tested at each fluid level by measuring the pressure according to manufacturer specifications (or according to literature instructions in the case of the Whitesides apparatus[9]). All measurement devices were kept at the level of the specimen.

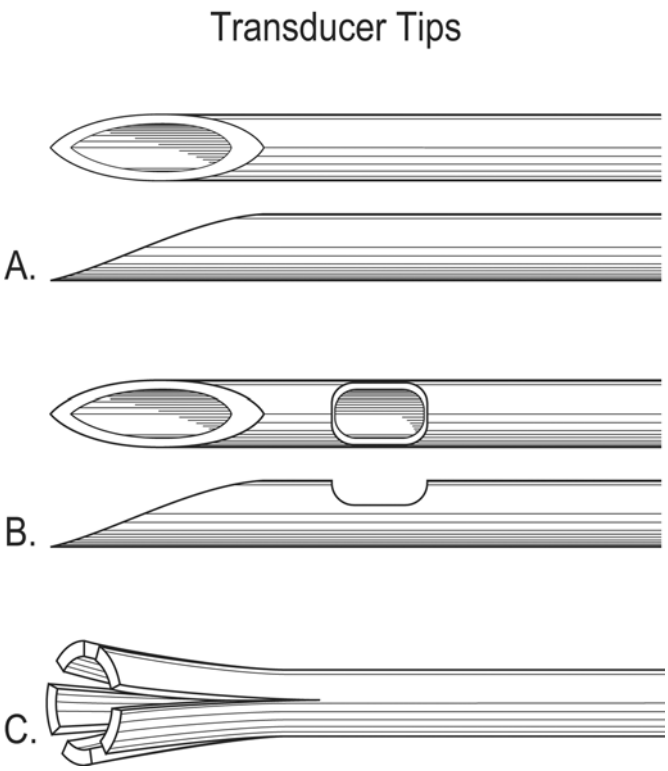

Fig. 2

A, Two views of an 18-gauge straight needle. *B,* Two views of an 18-gauge side-port needle. *C,* One view of a slit catheter.

The initial fluid level was 2.0 cm above the level of the needle (or catheter) test site. The fluid column was then filled

TABLE I Regression Data on the Setups Tested

	Slope		Intercept *(mm Hg [kPa])*		
Setup*	Mean and Standard Error	P Value	Mean and Standard Error	P Value	R^2 Value
SSP	0.98 ± 0.01	0.008	0.43 ± 0.39 (0.06 ± 0.05)	0.264	0.9816
SS	1.06 ± 0.03	0.014	10.30 ± 1.22 (1.37 ± 0.16)	<0.001	0.9358
SSL	1.05 ± 0.01	<0.001	–3.34 ± 0.26 (–0.45 ± 0.03)	<0.001	0.9953
ALSP	0.97 ± 0.00	<0.001	–1.25 ± 0.13 (–0.17 ± 0.02)	<0.001	0.9977
ALS	0.99 ± 0.01	0.538	21.85 ± 0.65 (2.91 ± 0.09)	<0.001	0.9749
ALSL	0.99 ± 0.00	0.001	0.56 ± 0.19 (0.07 ± 0.03)	0.004	0.9978
WSSP	0.98 ± 0.02	0.440	2.43 ± 0.94 (0.32 ± 0.13)	0.010	0.9115
WSS	1.26 ± 0.03	<0.001	–1.66 ± 1.29 (–0.22 ± 0.17)	0.199	0.9502
WSSL	1.24 ± 0.02	<0.001	3.02 ± 1.14 (0.40 ± 0.15)	0.009	0.9219

*SSP = Stryker device with side-port needle, SS = Stryker device with straight needle, SSL = Stryker device with slit catheter, ALSP = arterial line manometer with side-port needle, ALS = arterial line manometer with straight needle, ALSL = arterial line manometer with slit catheter, WSSP = Whitesides apparatus with side-port needle, WSS = Whitesides apparatus with straight needle, and WSSL = Whitesides apparatus with slit catheter.

incrementally with normal saline solution, and pressure measurements were obtained after each 2-cm addition to the fluid column height. The final fluid height was 110.0 cm. This process was repeated for a total of five trials for each combination of needle (or catheter) and measurement device. A new cube of ovine gluteal muscle was used for each trial.

The heights of the saline solution column at each testing point were translated into pressure data with use of standard known values for the densities of mercury, water, and saline solution at given temperatures[20]. The resultant converted pressures (expressed in mm Hg) were used as the control measures of defined pressure within the muscle tissue at each level.

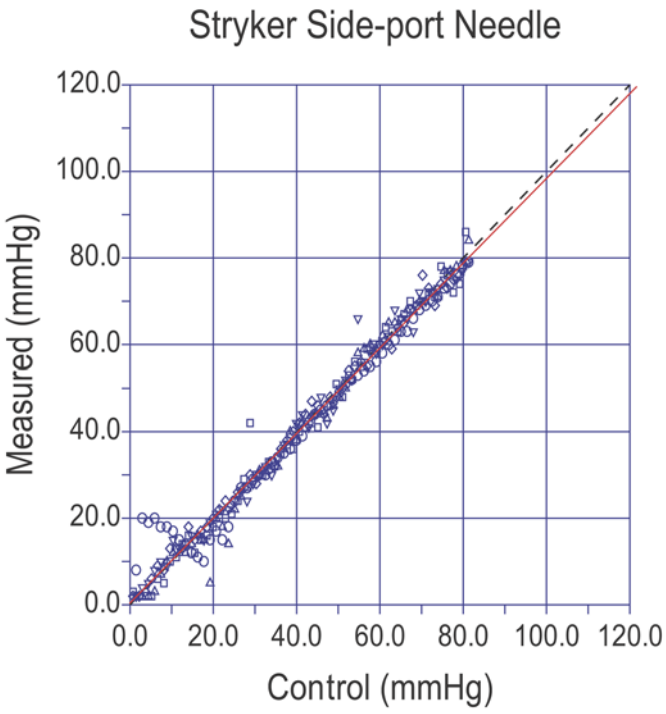

Fig. 3

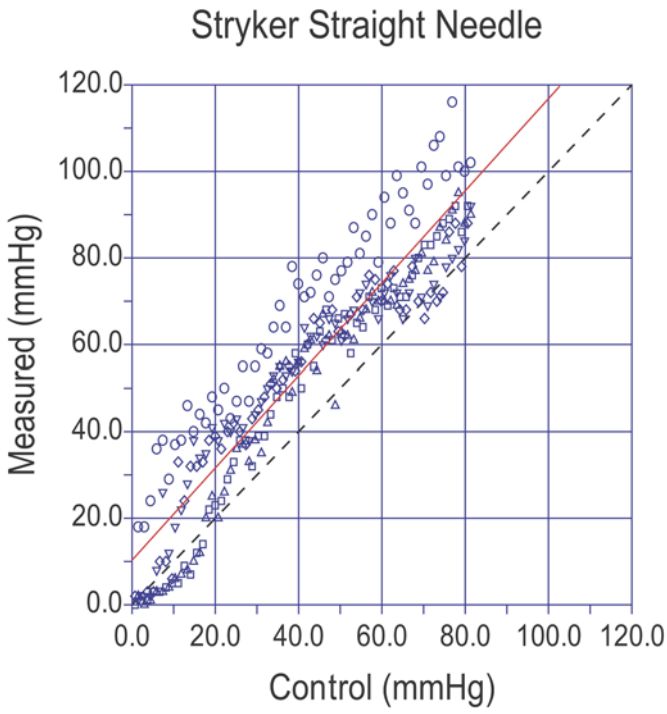

Fig. 4

Figs. 3 through 11 Illustrations depicting the slope and intercept associated with each setup. The five symbols represent separate trials, each with fifty-five points. The dashed line represents the so-called gold standard. **Fig. 3** The Stryker device with the side-port needle demonstrated good slope and correlation. **Fig. 4** The Stryker device with the straight needle demonstrated constant bias.

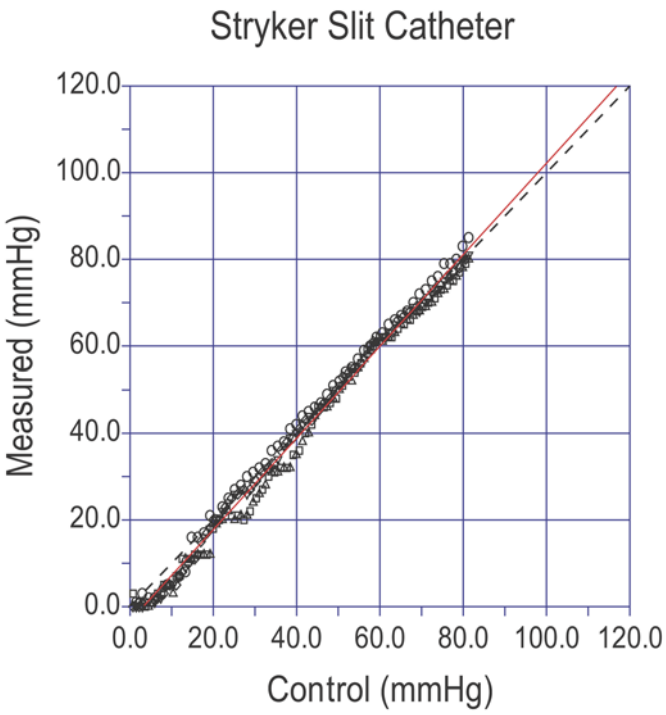

Fig. 5

The Stryker device with the slit catheter demonstrated excellent slope and negligible bias.

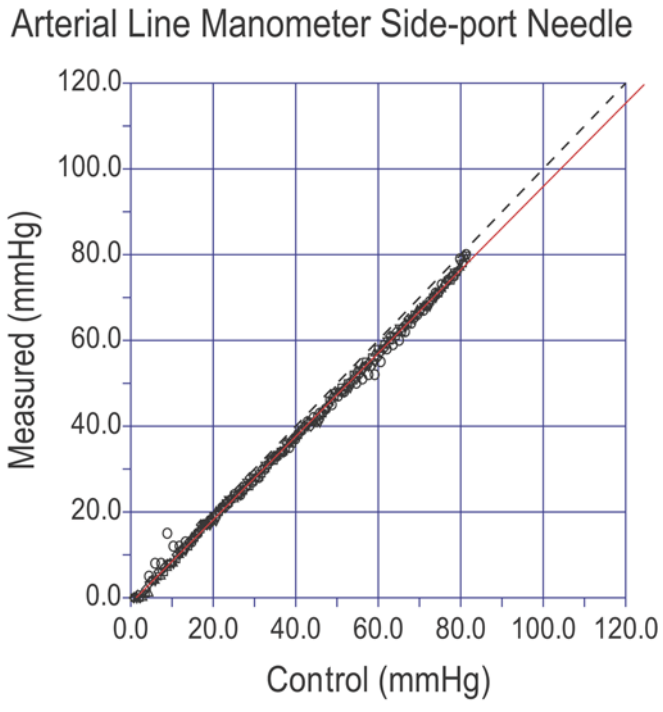

Fig. 6

The arterial line manometer with the side-port needle demonstrated excellent slope and minimal bias.

For each study apparatus, the actual measured pressures were plotted against the control pressure. Multiple regression analysis was performed, combining the data for each measured device. Constant bias is represented by the y-intercept (ideally equal to 0.0), and proportional bias is represented by the slope (ideally equal to 1.0). The confidence interval was set at 95%, corresponding with a significance level of $p < 0.05$.

Results

Regression data for the setups that were tested are presented in Table I. Plots of the data points and the corresponding best-fit lines are presented in Figures 3 through 11, with points from each trial set represented by different symbols. Most methods demonstrated excellent correlation ($R^2 > 0.95$); the arterial line manometer with the slit catheter showed the best accuracy ($R^2 = 0.9978$), and the Whitesides apparatus with the side-port needle showed the worst ($R^2 = 0.9115$).

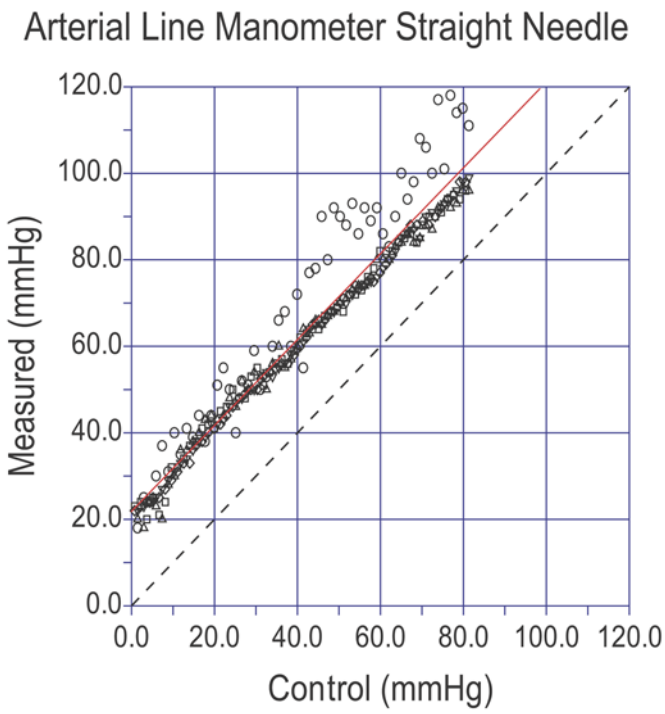

Fig. 7

The arterial line manometer with the straight needle demonstrated significant positive constant bias ($p < 0.001$).

In terms of constant bias (as indicated by the y-intercept), the Stryker device with the side-port needle tended to underestimate pressure slightly ($y = 0.43$ mm Hg [0.06 kPa], $p = 0.26$). This value was not significantly different from the standard of zero and represented the least bias in the present study. The Stryker device with the straight needle consistently overestimated pressure ($y = 10.30$ mm Hg [1.37 kPa], $p < 0.05$). The Stryker device with the slit catheter underestimated pressure ($y = 3.34$ mm Hg [0.45 kPa], $p < 0.05$). The arterial line manometer with the side-port needle showed

bias as well (y = 1.25 mm Hg [0.17 kPa], $p < 0.05$). Similar to the Stryker device with the straight needle, the arterial line manometer with the straight needle had considerable positive bias (y = 21.85 mm Hg [2.91 kPa], $p < 0.05$). The arterial line manometer with the slit catheter tended to overestimate pressure slightly (y = 0.56 mm Hg [0.07 kPa], $p < 0.05$). Two of the three Whitesides methods overestimated pressure, although to varying degrees (y = 2.43 mm Hg [0.32 kPa] for the Whitesides apparatus with the side-port needle [$p < 0.05$]; y = 1.66 mm Hg [0.22 kPa] for the Whitesides apparatus with the straight needle [$p = 0.20$]; and y = 3.02 mm Hg [0.40 kPa] for the Whitesides apparatus with the slit catheter

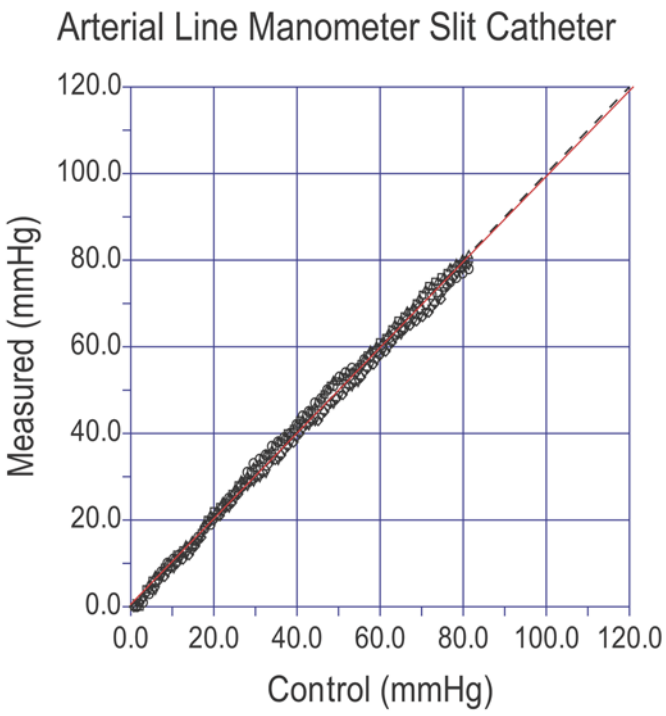

Fig. 8

The arterial line manometer with the slit catheter demonstrated minimal bias and excellent slope, with minimal standard error.

[$p < 0.05$]). The data for the Whitesides methods had the highest standard errors, consistent with the observed scatter in the data points.

For most groups, proportional bias (slope) varied significantly from the expected standard ($p < 0.05$). However, the slopes generated by the Stryker device with the side-port needle, the Stryker device with the slit catheter, the arterial line manometer with the side-port needle, the arterial line manometer with the slit catheter, the arterial line manometer with the straight needle, and the Whitesides apparatus with the side-port needle were within 5% of the standard control value (slope = 1.0), whereas those generated by the Stryker device with the straight needle, the Whitesides apparatus with the straight needle, and the Whitesides apparatus with the slit catheter showed the most deviation (+6%, +26%, and +24%, respectively).

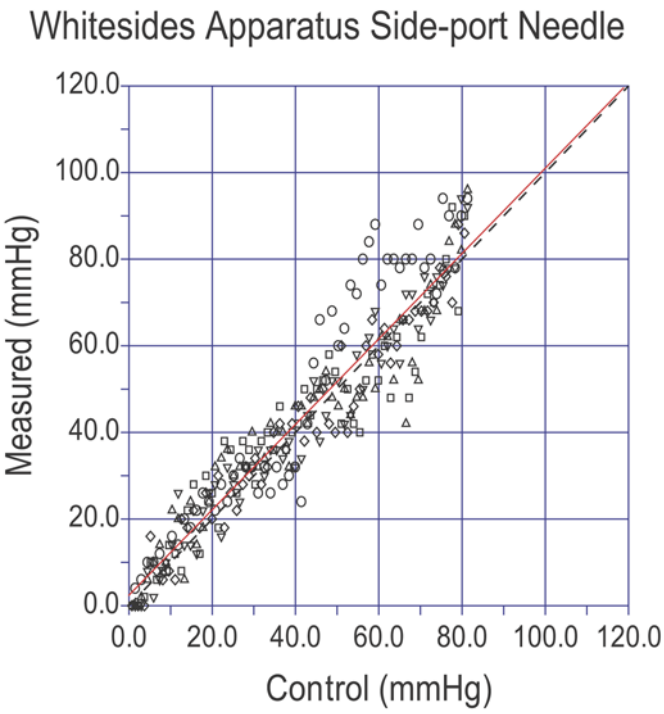

Fig. 9

The Whitesides apparatus with the side-port needle demonstrated a large amount of scatter. The large number of data points masks the lack of precision.

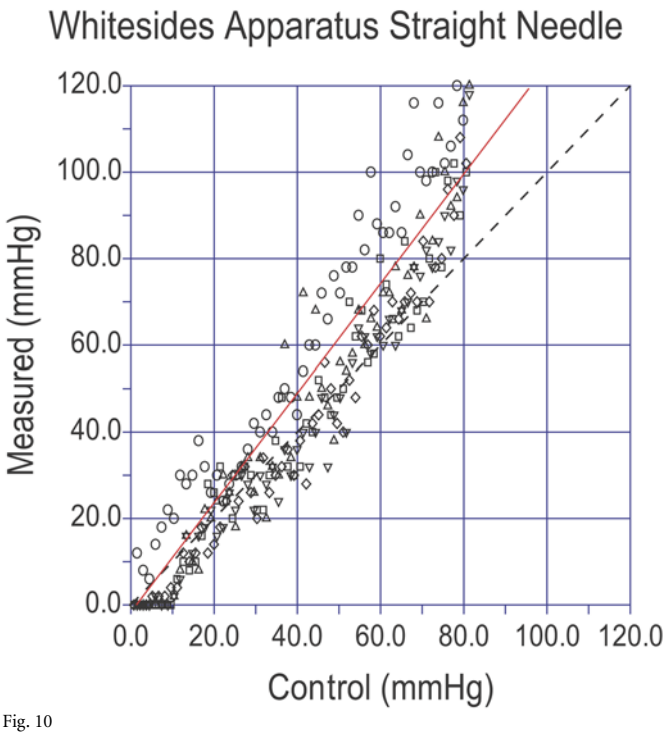

Fig. 10

The Whitesides apparatus with the straight needle demonstrated a large amount of constant and proportional bias as well as a lack of precision.

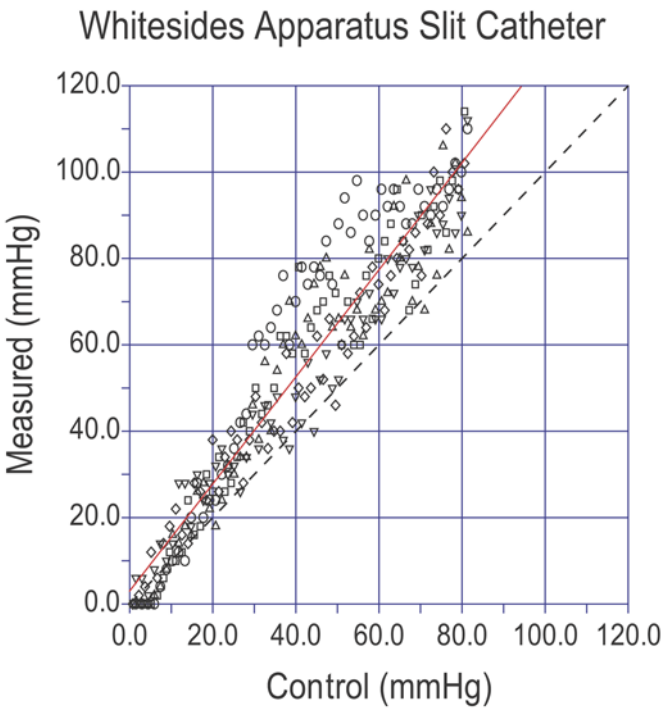

Fig. 11
The Whitesides manometer with the slit catheter also showed large amounts of constant and proportional bias along with scatter.

Discussion

The goal of the present study was to create a standard, reproducible method for testing tools that are used to measure compartment pressure. In the process of creating this standard method, we made a few assumptions. Using a graduated cylinder with a known height of fluid, we were able to measure multiple devices against a "known pressure." One assumption was that fresh ovine muscle that is subjected to a positive pressure environment generated by normal saline solution at 37°C has pressure transduction characteristics that are similar to those of human muscle tissue that is subjected to compartment pressure. The specific muscle type is not thought to influence the measured pressure; rather, it is most likely the interaction of tissue with the transducer tip and static occlusive properties that may favor one measurement device over another[21]. Two previous studies tested the accuracy of pressure measrements using a fluid-filled pressure column; neither included muscle tissue in the measurements using the fluid column[13,16]. However, we thought that measuring pressures within muscle tissue was more representative of the clinical scenario than simply measuring the pressure of a fluid column. We chose the measurement devices for this study on the basis of their wide availability. These methods are commonly used, and their use has been well described[9-15].

We used standard known conversion factors to convert the measured height of the column (expressed in cm of 0.9%

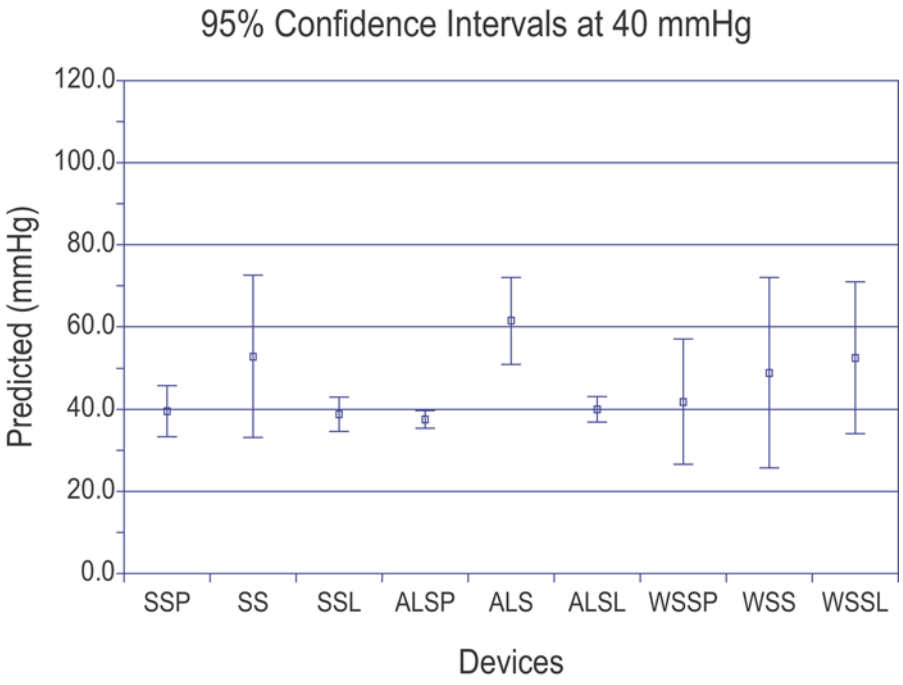

Fig. 12
This graph of the predicted measurement levels based on an actual pressure of 40 mm Hg demonstrates the accuracy and precision of each device (see text for descriptions of each device). SSP = Stryker device with the side-port needle, SS = Stryker device with the straight needle, SSL = Stryker device with the slit catheter, ALSP = arterial line manometer with the side-port needle, ALS = arterial line manometer with the straight needle, ALSL = arterial line manometer with the slit catheter, WSSP = Whitesides apparatus with the side-port needle, WSS = Whitesides apparatus with the straight needle, and WSSL = Whitesides apparatus with the slit catheter.

NaCl) to mm Hg so that the control data would be comparable with the experimental data. Our range of 1 to 110 cm of 0.9% NaCl corresponded to 1 to 81 mm Hg (0.13 to 10.80 kPa)[1-4,6]. We chose to use this "known pressure" as our independent variable rather than measuring the fluid directly with the needle or catheter and then repeating the measurement with the needle or catheter in the muscle tissue. Our aim was not to test each device against itself, but rather to test each device against a known standard pressure. While there should be pressure variations within the muscle itself, the use of measurements made at the same depth (1 cm) eliminates this variation. Furthermore, the density of muscle is slightly more than that of saline solution. However, the effect of the nearly negligible increase in constant bias would not be clinically relevant. Blood pressure also affects the pressure at which a compartment syndrome is diagnosed. We purposely chose a final pressure well above any accepted thresholds for the diagnosis of compartment syndrome to ensure that critical values would be well within our data set. Multiple regression analysis was used to correlate the dependent variable of pressure measurement with the independent variable of defined pressure while providing regression statistics (slope and y-intercept). Bias in the system was quantified by the y-intercept value in the regression data; for the ideal test apparatus, the intercept should approach 0 and the slope of measured pressures against defined pressures should approach 1.

The use of a straight needle repeatedly overestimated the measurement of intracompartmental pressure in the present study; this finding is consistent with previously published data[21]. The straight needle is easily clogged as it enters tissue and therefore measures a local milieu that is unlikely to be similar to the surrounding tissue. As the tissue enters the needle tip, the fluid inside the needle and tubing has no port for egress, and pressure in the system rises erroneously.

The Whitesides mercury manometer construct was the least accurate method tested in this study. We fastidiously followed the description of this system that is available in the literature[9]. The data were more variable with the straight needle ($R^2 = 0.9502$), the slit catheter ($R^2 = 0.9219$), and the side-port needle ($R^2 = 0.9115$) when compared with the other testing modalities. The correlation coefficient downplays the amount of actual error at each data point because of the large number of samples recorded. The individual data points varied by as much as 45 mm Hg (6.00 kPa) when compared with the control values. The mercury meniscus showed initial movements both well above and below the known pressure. We were unable to establish a pattern for our observed error with this device, and our experience was extremely frustrating. At times, the movement of the meniscus was very subtle and inconsistent. Furthermore, both the Whitesides apparatus with the straight needle and the Whitesides apparatus with the slit catheter demonstrated the greatest amounts of proportional bias (26% and 24%, respectively). Our difficulty with the mercury manometer parallels problems that have been reported in association with this construct[6-7].

Many of the test setups (all except the arterial line manometer with the straight needle and the Whitesides apparatus with the side-port needle) demonstrated significant proportional bias. One may consider that the bias could have been due to an error in the conversion factor. If an error in the conversion factor were present, all of the expected slope values would have been skewed either above or below 1.0. However, the slope values were distributed both above and below 1.0, indicating both positive and negative bias; this finding suggests that the conversion factor was accurately calculated on the basis of physical constants. Additionally, a simple average of the nine slopes yields a value of 1.06 ± 0.22 at the 95% confidence level. This finding provides further reassurance regarding the methodology of deriving the conversion factor a priori on the basis of physical constants. Nevertheless, most of the test setups had significant bias in the slope. The reason for this finding most likely lies in the extremely large data set, which in turn yielded narrow confidence intervals—well below that of clinical relevance. Most of the significant observed differences were within 2 to 3 mm Hg of the known pressure, which would not likely be clinically important.

The clinical implications of accurate diagnosis of compartment syndrome are well known. In situations in which a clinical diagnosis is not possible, as in the scenarios outlined above, a reliable objective method can aid in the determination of compartment syndrome. We have outlined a clinical picture for comparing the different devices. Because there is no standard definition of the absolute pressure above which the diagnosis of compartment syndrome is to be made, we have provided an illustrative example involving an arbitary value of 40 mm Hg (5.33 kPa) in this example (Fig. 12). At this theoretical known pressure, given the 95% confidence intervals calculated for our results, the Stryker device with the side-port needle (39.56 ± 6.23 mm Hg; 5.27 ± 0.83 kPa), the Stryker device with the slit catheter (38.82 ± 4.18 mm Hg; 7.05 ± 2.63 kPa), the arterial line manometer with the side-port needle (37.56 ± 2.15 mm Hg; 5.01 ± 0.29 kPa), the arterial line manometer with the slit catheter (40.02 ± 3.12 mm Hg; 5.34 ± 0.42 kPa), and the Whitesides apparatus with the side-port needle (41.82 ± 15.20 mm Hg; 5.57 ± 2.03 kPa) predicted pressures fairly accurately. However, the lack of precision of the Whitesides apparatus with the side-port needle places it outside the realm of clinically acceptable devices. The remaining test methods—the Stryker device with the straight needle (52.86 ± 19.71 mm Hg; 7.05 ± 2.63 kPa), the arterial line manometer with straight needle (61.51 ± 10.53 mm Hg; 8.20 ± 1.40 kPa), the Whitesides apparatus with the straight needle (48.89 ± 23.13 mm Hg; 6.52 ± 3.08 kPa), and the Whitesides apparatus with the slit catheter (52.53 ± 18.43 mm Hg; 7.00 ± 2.46 kPa)—overestimated the actual pressure to a clinically unacceptable degree. While the predicted values overestimate pressure, the lack of precision as seen by the wide confidence interval when using these tests highlights the real risk of underestimating pressure as well.

The present study had some limitations. One was the possibility of an error in measuring the height of the fluid column or the mercury manometer. The meniscus was easily visu-

alized, and any error would have been within 1 mm Hg for any given measurement. Furthermore, immediate temperature or atmospheric pressure changes could have affected our measurements. All measurements were made during two forty-eight-hour periods in the operating room area. Temperature and humidity are relatively constant in this location and should have had a negligible effect on our data. Our goal was to determine the overall accuracy of each device, not the accuracy of the device at a few known pressures. Thus, we performed five trials of fifty-five data points for each combination of device and needle or catheter. Our multiple regression analysis was extremely robust because of the large number of data points in the sample. This led to very small confidence intervals, so that small (clinically unimportant) differences in our known and measured data were significant.

The present study demonstrates that side-port needles (for acute and serial measurements) and slit catheters (for continuous measurements) are more accurate than straight needles are for the measurement of compartment pressures. Furthermore, on the basis of our experience in the present study and the resultant data, we cannot recommend the clinical use of the Whitesides apparatus because of its lack of precision. Both the arterial line and Stryker manometers demonstrated acceptable levels of accuracy and precision when used with either the side-port needle or the slit catheter. ■

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