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.
patients who were not suspected of having a compartment syndrome. 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, 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.

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 Intracompartamental Pressure Monitor System; Stryker, Kalamazoo, Michigan), and a Whitesides apparatus. 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). All measurement devices were kept at the level of the specimen.

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

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

*SPP = 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.

Fig. 3

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.
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 ($R^2 = 0.9115$).

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 ($y = 1.25 \text{ mm Hg} [0.17 \text{ kPa}]$, $p < 0.05$). Similar to the Stryker device with the straight needle, the arterial line manometer with the straight needle had considerable positive bias ($y = 21.85 \text{ mm Hg} [2.91 \text{ kPa}]$, $p < 0.05$). The arterial line manometer with the slit catheter tended to overestimate pressure slightly ($y = 0.56 \text{ mm Hg} [0.07 \text{ kPa}]$, $p < 0.05$). Two of the three Whitesides methods overestimated pressure, although to varying degrees ($y = 2.43 \text{ mm Hg} [0.32 \text{ kPa}]$ for the Whitesides apparatus with the side-port needle [$p < 0.05$]; $y = 1.66 \text{ mm Hg} [0.22 \text{ kPa}]$ for the Whitesides apparatus with the straight needle [$p = 0.20$]; and $y = 3.02 \text{ mm Hg} [0.40 \text{ kPa}]$ for the Whitesides apparatus with the slit catheter [$p < 0.05$]). 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).
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. Two previous studies tested the accuracy of pressure measurements using a fluid-filled pressure column; neither included muscle tissue in the measurements using the fluid column. 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.

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

![Image](https://example.com/figure11.png)

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

![Image](https://example.com/figure12.png)

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.
amount of actual error at each data point because of the large
testing modalities. The correlation coefficient downplays the
the mercury manometer parallels problems that have been re-
and inconsistent. Furthermore, both the Whitesides apparatus
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the control values. The mercury meniscus showed initial
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number of samples recorded. The individual data points var-
lished data.

The Whitesides mercury manometer construct was the
least accurate method tested in this study. We fastidiously fol-
the present study; this finding is consistent with previously pub-
lished data\textsuperscript{a}. 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 fol-
the description of this system that is available in the
literature\textsuperscript{b}. The data were more variable with the straight
needle (R² = 0.9502), the slit catheter (R² = 0.9219), and the
side-port needle (R² = 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 var-
yed 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 propor-
tional bias (26% and 24%, respectively). Our difficulty with
the mercury manometer parallels problems that have been re-
ported in association with this construct\textsuperscript{c-d}.

Many of the test setups (all except the arterial line
manometer with the straight needle and the Whitesides appa-
atus with the side-port needle) demonstrated significant pro-
portional 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 sug-
gests 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% con-
fidence 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 ob-
erved 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 com-
partment 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 determina-
tion 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 arbitrary
value of 40 mm Hg (5.33 kPa) in this example (Fig. 12). At this
theoretical known pressure, given the 95% confidence inter-
vals 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 arte-
rial 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) pre-
dicted pressures fairly accurately. However, the lack of preci-
sion 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 side-
port 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 col-
umn or the mercury manometer. The meniscus was easily visu-
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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 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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