Original Article

**A Comparison of Static Occlusion Setting Methods: Fluid Drop Rate and Pressure Drop**

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**ABSTRACT**

Tubing circuits primed with water were constructed on two roller pumps to characterize and compare two static methods of setting the occlusion on roller pumps (fluid drop rate and pressure drop rate).

Twelve separate experiments were performed in which PVC boot tubing diameters (1/2 in, 3/8 in and 1/4 in), roller position (each roller alone on a two roller pump) and roller occlusion (total occlusion to 0.004 in underocclusion) were varied. Fluid drop rates were measured from two heights (30 in and 1 m) above the pump head where drops of 1 cm and 1 in were timed for each occlusion setting. Pressure drop was measured by clamping the outlet tubing, injecting fluid into the tubing between the clamp and roller elevating the pressure to 300 mmHg and observing the rate that it dropped at each occlusion setting.

Fluid drop rate and pressure drop rate were positively correlated at all occlusion settings and tubing sizes ($p < 0.001$). Using a single roller occlusion and an optimal fluid drop rate of .5 to 1.5 cm/min. at 30 in height, pressure drops (mmHg/min.) were (mean± SD); 1/2 in tubing = 263 ± 33, 3/8 in= 241 ± 52, 1/4 in= 264 ± 11. For a fluid drop rate of 1.27 to 3.81 cm/min. at 1 m height, pressure drops were (mean ± SD); 1/2 in= 266 ± 33, 3/8 in=278 ± 17, 1/4 in=274 ± 20. The occlusion settings or occlusion gap varied significantly ($p < 0.001$) between pumps and tubing sets. Thus, it appears as though pressure drop rate can predict fluid drop rate at just non-occlusive pump settings; however, the occlusion should be rechecked every time a different pump or boot tubing is used.

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INTRODUCTION

The proper occlusion setting on positive displacement roller pumps has been the subject of debate since they were first used for propelling blood during hemodialysis and cardiopulmonary bypass. Investigators first thought that a roller or finger pump set just occlusive was preferable (1, 2), guaranteeing reliable forward flow with minimal hemolysis. They soon realized, however, that in addition to fat emboli, high pressure suction and blood-gas interfaces in oxygenators and reservoirs, roller pumps also contribute to hemolysis during cardiopulmonary bypass. According to several studies (3, 4), the difference between barely non-occlusive and just occlusive pump settings appears to be a major factor in pump induced mechanical damage of formed elements in the blood. Additionally, it was found that over occlusion results in tubing spallation and the release of microscopic particles into the circuit (5). Most investigators today agree that a just non-occlusive pump setting is preferable, especially in instances where long term cardiopulmonary support or ECMO is indicated (6).

The method most often described for setting the occlusion on a roller pump is the fluid drop rate technique. This involves advancing a column of fluid to a certain height above the pump head, with the only impediment to gravity drainage being the point at which tubing is compressed by the pump roller. The height to which the fluid is advanced is dependent on the anticipated outflow or mean aortic pressure. The occlusion is then adjusted by moving the roller away from the raceway so that the fluid column drops at a prescribed rate. Complete occlusion is defined as the roller setting which causes the column of liquid to remain at a constant level indefinitely, any lessening of which allows the liquid to pass through. To set a just non-occlusive pump, the fluid drop rate and height of the fluid column above the pump can be varied depending on the degree of non-occlusiveness desired. Both tight occlusion settings, (1 cm/min at 30 in (7), 1 inch/min at 1 m (6, 8, 9), and loose occlusion settings (2 cm/5 s at 60 cm (4,10) have been described in the literature.

Noon et al (3) sought alternatives to the fluid drop rate method because, “The standard drop rate technique, except for identifying the exact point of occlusion, is poorly reproducible...it fails entirely at settings under occlusive by 0.008 in or more when the drop rate is so great that even extrapolation from stop watch times proves unreliable.” They describe other techniques including micrometer measurements of the gap between roller and the horseshoe stator, and measurements of electrical current drop as the pump responds to lesser occlusions. Unfortunately these methods alone did not prove to be any more useful or convenient than the fluid drop rate technique (3).

Since an occlusion gap causes a column of fluid on the outlet of a pump to drop due to retrograde leakage, the gap should also cause a pressure drop if the column of fluid were pressurized. The focus of this study will be on determining whether this pressure drop rate technique would be more sensitive, reliable and easier to use than the popular fluid drop rate method of setting roller occlusion.

MATERIALS AND METHODS

Figure 1 depicts the circuit used for each experiment. A 1600 ml reservoir\(^a\) was suspended at the same level as a double roller pump\(^b\), providing the outlet and inlet ports of a tubing loop. All of the tubing (PVC)\(^c\) used in this protocol was 3/32 in thick except for the 1/4 in tubing which was 1/16 in thick. The reservoir, as well as the tubing connecting the reservoir outlet to the boot tubing, was re-used for each circuit. A 6 ft loop of tubing with an attached metal straight edge meterstick was connected to the boot outlet and reservoir inlet. Luer lock connectors were used to connect a pressure box\(^d\) and a manifold / shunt distal to the pump head but before the meterstick. The bottom of the meterstick (0 m) was placed at the same height as the pump head. The circuit was primed with enough room temperature tap water so that the level in the reservoir was at the same height as the pump.

To measure fluid drop rate, the outlet tubing was opened to

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\(^a\) Medtronic MVR 1600, Medtronic Cardiopulmonary, Anaheim CA 92807
\(^b\) Product designation 10-25-00, Sorin Biomedical, Irvine CA 92713
\(^c\) Baxter Healthcare, Bentley Division, Irvine, CA 92714
\(^d\) DLP Pressure Display 60,000, Grand Rapids MI 49501
air and the fluid advanced to the desired height (1 m or 30 in) by injecting fluid into the manifold. For each occlusion setting a drop of 1 cm was timed and this was repeated five times.

To measure pressure drop, the outlet tubing filled with fluid was clamped with a tubing clamp above the meterstick and the instantaneous pressure was increased to 400 mmHg by injecting fluid into the circuit proximal to the clamp via the manifold. The pressure was allowed to drop and as the pressure reached 300 mmHg a timer was started and allowed to count down for one minute. At the end of one minute the pressure was noted and subtracted from 300 giving a change in pressure per minute. This was repeated five times. At the beginning of each experiment and period of occlusion was lessened by turning the thumbwheel one click (15 microns) at a time for a total of seven clicks (seven being the least occlusive) as pressure drop and drop rate measurements were taken at each click. These measurements were recorded for each roller alone which was placed at the raceway midpoint. This was repeated with a column of fluid filled to a height of 1/2 in. A column of fluid was advanced to a height simulating a neonatal tubing circuit with 1/2 in boot and 3/8 in loop. To examine the difference between rollers, pumps and tubing pieces, a column of fluid was advanced to a height of 1/4 in. This was repeated using two pumps and two boot tubing sets.

Three different circuits were constructed, the first simulating a neonatal tubing circuit with 1/4 in boot and 1/4 in loop, the second a pediatric circuit with 3/8 in boot and 1/4 in loop and the third an adult circuit with 1/2 in boot and 3/8 in loop. To examine differences between rollers, pumps and tubing pieces, each circuit was tested using two pumps and two pieces of boot tubing from the same roll.

For each circuit the following protocol was employed. A column of fluid was advanced to a height of 1 m and the pump was set just occlusive (no pressure drop or fluid level drop in 10 minutes). The occlusion was lessened by turning the thumbwheel one click (15 microns) at a time (1 click being the least occlusive) as pressure drop measurements were taken at each click. These measurements were recorded for each roller alone which was placed at the raceway midpoint. This was repeated with a column of fluid filled to 30 in above the pump. Fluid administered via the manifold served to increase pressure and fluid in the tubing without having to move the roller. A total of 12 experiments were performed utilizing the three tubing circuits, two pumps and two boot tubing sets.

Multiple factor analysis of variance (BMDP statistical software, version 7.0) was used to compare and contrast results obtained using different tubing sets (n = 2), roller positions (n = 2) and pumps (n = 2). Correlative analysis (Microsoft Excel) was used to determine the relationships between the variables in the experiment.

**RESULTS**

Analysis of the data reveals three relationships. First, the fluid drop rates from both 30 in and 1 m are positively correlated (Table 1B) with pressure drop rates for each boot tubing size. As the occlusion is lessened, the fluid level decrease is comparable to the decrease in pressure. Note that as tubing diameter decreases, the correlation with pressure drop increases (1/2 in tubing at 30 in r = 0.42 vs. 1/4 in tubing at 30 in r = 0.55). To describe this relationship in clinically useful terms, pressure drop rates were averaged over an optimal fluid drop range based on the 1 cm/min drop at 30 in and 1 in/min drop at 1 m discussed in the methods (Table 2). At 30 in, a range of 0.5 - 1.5 cm/min was considered optimal while at 1 m an optimal range of 1.27 - 3.81 cm/min was used for each tubing size. The pressure drop rates were in approximately the same range for all tubing sizes used and corresponded to an extrapolated 32 - 49 mmHg pressure drop every 10 sec. Note that as the tubing diameter decreases, the standard deviation of the mean also decreases.

Secondly, the fluid drop rate from 30 in is highly correlated (r = 0.93) (Table 1) with the drop rate from 1 m for all tubing sizes. Figure 2 demonstrates this relationship, showing a high correlation and regression line linking drop rates from 30 in and

| Table 1. Correlation Analysis of Experimental Variables (A) Gap = Click number (1-7), (B) Pressure Drop Rate (mmHg/min), (C) Fluid drop rate (cm/min). All correlations are significant p<0.05. |
|---|---|---|---|
| (A) | (B) | (C) |
| Pressure Drop Rate | Fluid Drop Rate (1 m) | Fluid Drop Rate (30 in) |
| ALL TUBING SIZES | 0.95 | 0.52 | 0.49 |
| Fluid Drop Rate (1 m) | 0.47 | 0.44 | 0.93 |
| Fluid Drop Rate (30 in) | 0.54 | 0.56 | 0.49 |
| 1/2 in BOOT TUBING | 0.94 | 0.44 | 0.47 |
| Pressure Drop Rate | 0.40 | 0.42 | 0.98 |
| Fluid Drop Rate (1 m) | 0.54 | 0.56 | 0.49 |
| Fluid Drop Rate (30 in) | 0.95 | 0.51 |
| 1/4 in BOOT TUBING | 0.56 | 0.60 |
| Pressure Drop Rate | 0.51 |
| Fluid Drop Rate (1 m) | 0.95 |
| Fluid Drop Rate (30 in) | 0.98 |

* BMDP Statistical Software Inc., Los Angeles, CA 90025
* Microsoft Corporation, One Microsoft Way, Redmond WA 98052
The measured pressures exerted by the fluid columns were 64 ± 4 mmHg at 1 m and 45 ± 5 mmHg at 30 in.

The third relationship described by the results is the interaction between the intervention (increasing the underocclusion gap or increasing the click number) and the pressure drop and fluid drop. Table 1 and Figure 3 demonstrate that pressure drop rate correlates highly (r >0.90) with underocclusion gap for all tubing sizes. Fluid drop rates from 30 in and 1 m correlate less positively with occlusion gap (Figures 4 and 5).

A multifactor analysis of variance compared rollers (n = 2), pumps (n = 2) and tubing sets (n=2) in a range defined by the underocclusion gap necessary to affect the prescribed drop rate (0.5 - 1.5 cm/min). The dependent variable was the underocclusion gap. Table 3 shows that rollers 1 and 2 were not significantly different with all tubing sizes. Pumps 1 and 2 had significantly different occlusion gaps in the described range with 1/2 in and 3/8 in boot tubing but not with 1/4 in tubing. Results using tubing sets 1 and 2 were significantly different with 1/2 in boot tubing but not for 3/8 in and 1/4 in boot tubing. As the tubing interior diameter decreased, differences between pumps, rollers and tubing sets became less evident.

**DISCUSSION**

**Fluid drop rate vs. Pressure drop rate**

One of the goals of this set of experiments was to develop a working relationship between fluid drop rate and pressure drop rate. We found the two static occlusion setting methods to be significantly correlated and comparable. This relationship was only tested in the just underocclusive range specified in the methods (0 - 0.004 in gap). The correlation was found to increase as the tubing interior diameter became smaller indicating that comparisons between pressure drop rate and fluid drop rate may be more reliable with smaller boot tubing.

The optimal fluid drop rate most referenced is a drop of 1 cm/min from a fluid height of 30 in (7) and 1 in/min from 1 m (6,8,9) above the pump. It is thought that just underocclusive settings maintain flow accuracy while at the same time minimizing the tubing wall interactions and hemolysis found with totally occlusive pumps. Based on this optimal fluid drop rate, ranges of 0.5 - 1.5 cm/min from 30 in and 1.27 - 3.81 cm/min from

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**Table 2. The extrapolated optimal pressure drop rate (mmHg/10 seconds) (mean ± SD) from 300 mmHg was defined by optimal fluid drop rate from heights of 30 in and 1 m with 1/2 in, 3/8 in and 1/4 in boot tubing.**

<table>
<thead>
<tr>
<th>Fluid drop rate (cm/min)</th>
<th>1/2 in Boot</th>
<th>3/8 in Boot</th>
<th>1/4 in Boot</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 in Height (0.5 - 1.5)</td>
<td>43 ± 5</td>
<td>40 ± 8</td>
<td>44 ± 2</td>
</tr>
<tr>
<td>1 m Height (1.27 - 3.81)</td>
<td>44 ± 5</td>
<td>46 ± 3</td>
<td>46 ± 2</td>
</tr>
</tbody>
</table>

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**Figure 2: Fluid drop rate: 1 m vs. 30 in**

**Figure 3: Pressure drop vs. underocclusion gap**
1 m were used to analyze the data. Pressure drop rates that fell within these ranges were averaged to produce a pressure drop rate that would approximate an optimal occlusion. Results from all tubing sizes showed a pressure drop rate of 32 - 49 mmHg / 10 sec can be used to estimate an optimal occlusion setting once the pump is primed.

Underocclusion gap vs. Pressure drop rate and fluid drop rate

Personal communications with Sorin Biomedical reveal that the thumbwheel occlusion setting device is calibrated to move the rollers 15 microns with each click of the dial. From a point of total occlusiveness, the underocclusion gap was increased one click at a time for a total of seven clicks. At each click, pressure drop rate and fluid drop rate were recorded. As shown in Figure 3, pressure drop rate correlated highly for all tubing sizes with click number \( r = 0.90 \), while fluid drop rate from 30 in and 1 m showed a lower correlation (Figures 4 and 5). To quantify these small underocclusion gaps, pressure drop may be a more sensitive and/or reliable measure of occlusion. The fluid drop rate method appears to be an all or none method of measurement: at very tight gaps it drops at almost an imperceptible rate and at increased gaps it drops too rapidly to measure accurately. The pressure drop rate method succeeds in identifying very small occlusion gaps more accurately, but like the fluid drop rate method, drops very rapidly as occlusion is lessened beyond 0.004 in gap.

The fluid drop rates from 30 in (76 cm) and 1 m were highly correlated as would be expected (Figure 2). An increase of 24 cm in height above the pump head nearly doubled the fluid drop rate for each gap when compared with the fluid drop rate at 30 in. This was due to the increase in hydrostatic pressure exerted by the column of fluid. Changes in the interior diameter of the loop tubing had no additional effects on drop rate. An advantage to measuring fluid drop rates from 1 m was that a drop of 1 in/min is easier to visually gauge because the fluid moves somewhat faster. However, with most tubing packs used clinically, it would be difficult to raise the pack 1 m above the pump. Additionally, fluid advanced to 1 m exerts a hydrostatic pressure of approximately 64 mmHg which may more closely reflect mean aortic pressure than the hydrostatic pressure of 48 mmHg found at 30 in height.

Comparisons between pumps, tubing sets and rollers

Analysis of the variance between pumps, duplicate tubing sets and rollers was made to determine if optimal fluid drop rates were associated with a fixed optimal underocclusion gap that could be applicable for all tubing and pumps. If this were the case, once an optimal gap is determined, it could be utilized for all pumps and tubing sets. The data from this experiment reveals that this assumption is not always true. The optimal occlusion gaps from the two pumps tested differed significantly when using 1/2 in boot and 3/8 in boot but did not differ significantly when using the smaller 1/4 in boot tubing (Table 3). Differences between duplicate tubing sets cut from the same roll were found only with 1/2 in boot tubing. It appears as though the optimal gap is more variable between pumps and tubing sets when using larger boot sizes. This is perhaps due to a differing geometry of the gap with large boot interior diameters compared with boots with smaller interior diameters. Each roller on the pump was closely approximated with the other and there was no significant difference between rollers. It is still advisable however to check the occlusion using each roller individually to rule out any variations that may occur.

Table 3. Analysis of variance between roller positions (1 and 2), pumps (1 and 2) and tubing sets (1 and 2) for each tubing size. The dependent variable was underocclusion gap (1 - 7).

<table>
<thead>
<tr>
<th>Variables</th>
<th>1/2 in Boot</th>
<th>3/8 in Boot</th>
<th>1/4 in Boot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rollers 1 &amp; 2</td>
<td>N.S.</td>
<td>N.S.</td>
<td>N.S.</td>
</tr>
<tr>
<td>Pumps 1 &amp; 2</td>
<td>&lt;.001</td>
<td>&lt;.01</td>
<td>N.S.</td>
</tr>
<tr>
<td>Sets 1 &amp; 2</td>
<td>&lt;.05</td>
<td>N.S.</td>
<td>N.S.</td>
</tr>
</tbody>
</table>

Figure 4: Fluid drop rate from 30 in vs. underocclusion gap

- **Figure 4**: Fluid drop rate from 30 in vs. underocclusion gap

- **Table 3**: Analysis of variance between roller positions (1 and 2), pumps (1 and 2) and tubing sets (1 and 2) for each tubing size. The dependent variable was underocclusion gap (1 - 7).
Considerations
This experimental design took into account many variables but excluded several. The fluid drop rates described in the literature are meant to be measured using an asanguinous prime, but they describe the proper occlusion for blood prime (6,7,8,9). Pressure drop may not accurately predict occlusion setting with a blood prime. The increased viscosity of the blood may impede retrograde flow through the rollers and alter pressure drop. We cannot reliably state an optimal occlusion gap in this study without using micrometer calipers to verify the calibration of the thumbwheel occlusion setting device. The micrometer roller adjustments made during the study were assumed to be accurate and each click equal in measure.

Clinical applications
These results suggest that the static pressure drop rate method may be comparable, if not more sensitive and reliable, than the fluid drop rate method of setting the occlusion. In the clinical setting it would offer an additional method of verifying the occlusion on a primed pump before going on bypass. More importantly, it would provide a way of checking the occlusion when conducting long term cardiopulmonary support. For the just underocclusive settings recommended for perfusion today, the static pressure drop rate and fluid drop rate can both be used to determine occlusiveness. This data shows that pressure drop rate may be more sensitive with very small underocclusion settings (0 - 0.004 in) than the fluid drop rate.

REFERENCES