Research Article

Investigation of Cerebrospinal Fluid Flow Characteristics Through Adult and Pediatric Shunt Tubing

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Abstract

Shunt malfunction in adult and pediatric populations continues to be a perplexing problem. We examined artificial cerebrospinal fluid flow differential between adult and pediatric shunt systems. Flow through adult and pediatric-sized catheters was compared with artificial CSF using shunt systems containing new catheters, explanted catheters, 2-piece catheters, 3-piece catheters and with varying protein levels. The adult and pediatric explanted catheters were: three different lengths (90cm, 52cm, and 25 cm) and were compared to new catheters of the same lengths. New pediatric-sized catheters have a statistically significant increase in resistance to flow when compared to adult catheters of the same lengths (p=0.0001). Explanted pediatric catheters had a slight increase in resistance to flow when compared to adult catheters of similar lengths. For both adult and pediatric-sized catheters, as concentration of protein increases, resistance to flow decreases (p<0.05). Resistance to flow in pediatric cerebrospinal fluid shunt systems containing 2-piece catheters, 3-piece catheters is higher than in comparable adult cerebrospinal fluid shunt systems. First study to examine the difference in flow dynamics between adult and pediatric shunts. The results suggest important finding that minimum pieces of shunts should be used to decrease chances of blockage.

ABBREVIATIONS

CSF: Cerebrospinal Fluid; aCSF: Artificial CSF

INTRODUCTION

Although a great deal of research has been done to examine the causes of cerebrospinal fluid (CSF) shunt system failure, it still remains a perplexing problem. Current research has focused on examining causes of shunt malfunction and revision rates [1-11]. The common causes associated with shunt malfunction include valve malfunction, distal and proximal catheter obstruction, distal catheter disconnection, and infection. A retrospective chart review of pediatric patients with at least a 15 year follow up period found proximal and distal catheter occlusions to be some of the most frequent causes of shunt failure or malfunction. That study also reported more than half of the shunt failures occurred within the first year with patients requiring an average of 2.66 revisions over the course of their treatment [12]. Another group examined the etiology of shunt failures over seven years and reported that 14% of failures occurred within the first month and that premature infants demonstrate the shortest shunt system survival [13].

While a majority of work has been done examining the causes of shunt failure itself, we hoped to better understand how changing different components of a shunt system affects the flow of CSF. It is known that the addition of a valve in series with a catheter increases the resistance up to 200% [9]. In previous work we investigated how the age of shunt systems, number of shunt accessories, length of catheters, and addition of protein within the systems affected resistance to flow [14-15]. We concluded that the addition of shunt accessories like straight connectors, length of the catheter, and age of the catheters increased the resistance to CSF flow and increasing amounts of protein decreased resistance to flow. In that study we compared changes in the flow of CSF with the addition of anti-siphon valves. When we compared the change in resistance with the addition of a valve, our results were consistent with previous work [15]. We also found that the addition of protein resulted in an arithmetic decrease in resistance to flow within the experimental shunt systems [14]. According to Pousielle’s Law, the flow through a system should increase with a larger radius of shunt tubing and the corresponding resistance to flow should decrease [16]. Therefore, the inner radius of a shunt system could dramatically affect how shunt systems function.
With the goal of reducing shunt system malfunction, we examined the hydrodynamic resistance and flow in both adult and pediatric shunt systems. In our study we examined the difference in resistance to flow between new and explanted adult and pediatric shunt systems with and without the addition of shunt accessories. We also compared the resistance to flow in adult and pediatric systems after adding additional increments of albumin to the CSF.

**MATERIALS AND METHODS**

New CSF shunt tubing was donated by Medtronic (Minneapolis, Minnesota). The Medtronic PS Medical adult-sized catheter tubing had an outer diameter of 2.5 mm, an inner diameter of 1.3 mm, and was originally 120 cm in length. The Medtronic PS Medical pediatric-sized catheter tubing had an outer diameter of 2.1 mm and an inner diameter of 0.7 mm. Straight connectors, donated by Codman (Raynham, Massachusetts) had beveled tips with a length of 11.1 mm and an inner diameter of 1.0 mm, and an outer diameter of 1.9 mm. All catheters tested were open-ended catheters. No slit valve catheters were used.

With the approval of the institutional review board, explanted catheters were obtained from patients undergoing non-infected CSF shunt revision surgery. Original diagnosis, length of catheter, model number and manufacturer of the acquired shunt were recorded. When infection was suspected at the time of surgery, the catheter was excluded from the study. Shunt specimens were tested while this study was active between May, 2012 and August, 2013.

**Artificial CSF**

Artificial CSF (aCSF) was made using the concentrations described by L Sendelbeck [17]. One liter of distilled water (100 mL aliquots) was mixed with 126 mM sodium chloride, 3 mM potassium chloride, and 1.25 mM monosodium phosphate until completely dissolved. Subsequently, 2 mM magnesium chloride and 2 mM of calcium chloride were added and allowed to dissolve; and 26 mM sodium bicarbonate and 10 mM dextrose were added and allowed to dissolve. In experiments where the effect of protein concentrations were being examined, bovine serum albumin was added to the artificial CSF solution to reach the appropriate concentration levels of 0.5 g/L, 2 g/L, 5 g/L, and 10 g/L.

**Measurement of Resistance to Flow**

A water bath system as pictured in Figure (1) was maintained at 37 ± 2 °C. Manometers were placed at each end of the water bath with a constant height of ± 2 mm. A flask with a redundant catheter containing 350 mL of aCSF was connected to the proximal CSF drainage catheter and placed in the water bath. The flask and catheter were constant in all experiments and the catheter was of adequate length to ensure aCSF was equilibrated to the temperature of the water bath. The proximal end of the catheter was attached to the proximal manometer. The distal end of the catheter was then attached to the distal manometer. All air was purged from the system before each trial began and the flask was rinsed with distilled water while the aCSF was made. The pump was set to provide flow of 1.5 mL per hour. After one hour the water column heights of the proximal and distal manometer were read and recorded, as well as the total volume of aCSF remaining in the beaker. Between each consecutive trial, distilled water was used to clean out the catheter to help remove any possible residual protein inside the catheter by use of a stopcock and syringe located at the proximal end of the apparatus (Figure 1).

**Adult and pediatric-sized new and explanted tubing**

To examine the effects of albumin on aCSF flow, new adult and pediatric-sized distal catheter tubing was cut to 25 cm, 52 cm, and 90 cm. The specific lengths of catheter were chosen to match lengths of explanted catheters. For each length the resistance was measured using the above procedure for a control group, and then using aCSF with varying albumin concentrations of 0.5 g/L, 2 g/L, 5 g/L, or 10 g/L. The explanted catheters of the corresponding lengths were also tested with aCSF, 0.5 g/L, 2 g/L, 5 g/L, or 10 g/L. Resistance to flow was measured three times at each protein concentration and length of catheter.

**Adult and pediatric systems with the addition of straight connectors**

To compare flow through adult and pediatric 2-piece and 3-piece shunt systems, adult and pediatric catheter tubing was cut to 52 cm. To create 2 piece systems, one straight connector was added to the 52 cm shunt tubing and subsequently two straight connectors were added to the 52 cm catheters to create 3-piece shunt systems. Three experiments for the adult and pediatric 2-piece and 3-piece shunt systems were completed for a total of 18 experiments including the control group.

**Determination of resistance to flow**

The following variables were recorded during the measurement of resistance: starting volume of aCSF, ending volume of aCSF, total volume of aCSF used, height of the water column in proximal manometer, height of water column in distal manometer.

Using Poiseuille’s Equation assuming a constant velocity, the flow for CSF (a Newtonian fluid) through the CSF shunt system was calculated. In this equation, \( Q = \frac{r^4}{8\eta l} \cdot \frac{P}{\Delta h} \)

\( r = \) radius of the catheter,
\( l = \) length of distal catheter, and
\( \eta = \) viscosity of the fluid.

![Figure 1 Schematic of shunt flow system in a water bath maintained at 37° ± 2°C.](image)
A prescribed viscosity of CSF at 0.79 mPa·s (mPa=milipascals, s=seconds) was used for the viscosity in the calculation of flow throughout the system.

\[ Q = \frac{(P_{\text{proximal}}-P_{\text{distal}}) \pi r^4}{8l\eta} \]

Poiseuille's law states that the volume of flow through an incompressible fluid through a circular tube is equal to \( \frac{\pi}{8} \) times the pressure differences between the ends of the tube, times the fourth power of the tube’s radius divided by the product of the tube’s length and the dynamic viscosity of the fluid [15]. Using the data obtained and Poiseuille’s law shown in this equation, the resistance to flow was calculated for each trial. According to Poiseuille’s Law resistance to flow is equal to \( Q/(P_{\text{proximal}}-P_{\text{distal}}) = \frac{8l\eta}{\pi r^4} \). Therefore we were able to calculate resistance to flow for each trial by measuring the flow of aCSF through each system over one hour and dividing that by the change in pressures between the proximal and distal manometers.

RESULTS

Adult vs pediatric-sized catheters

Mean resistance to flow through pediatric-sized catheters and adult-sized catheters was compared after three runs of adult and pediatric shunt tubing at 25 cm, 52 cm, and 90 cm were completed. When all averages were combined for adult and pediatric catheters, new pediatric catheters had a statically significant (p<0.05) increase in mean resistance to flow when compared to adult catheters (Figure 2a). A similar trend was noticed in explanted catheters but not found to be statistically significant (Figure 2b).

The effect of albumin on adult and pediatric catheters

Resistance to flow was measured in new adult and pediatric at three different catheter lengths using five different protein concentrations (aCSF, 0.5 g/L, 2 g/L, 5 g/L, 10 g/L). The results of these experiments are shown in Figures (3a-c). With the addition of increasing amounts of protein to adult and pediatric shunt systems a statistically significant (p<0.05) arithmetic decrease in mean resistance to flow is observed. This same trend was seen when protein was added to the available 90cm and 25cm explanted adult and pediatric systems (Figure 4).

Changes in resistance with the addition of shunt accessories

In addition to comparing the resistance to flow between adult and pediatric catheters with and without the addition of albumin the changes in resistance to flow of 2-piece and 3-piece pediatric catheter system was measured (Figure 5). For a 90 cm 2-piece shunt system and a 90cm 3-piece shunt system, the mean resistance to flow was measured. There was a statistically significant increase in resistance to flow with the addition of one and two connectors to a 90 cm new pediatric shunt system. In addition, resistance in 2-piece pediatric catheters was markedly less than the mean resistance to flow in 3-piece pediatric catheter systems of the same length.

Adult and pediatric catheter systems after the addition of straight connectors

New adult and pediatric shunt systems with one or two connectors were examined in the laboratory. The mean resistances to flow after the application of the Bonferroni post-hoc correction for each condition are shown in Table (1). The mean resistance to flow increased after the addition of one and two connectors when compared to the control (p<0.05). However, there was no statistical increase in flow between systems with one or two connectors (Table 1).

After resistance to flow was measured in adult and pediatric systems containing shunt connectors we were able to examine the changes in flow between adult and pediatric sized tubing. When the average resistance to flow was compared between adult and pediatric shunt systems pediatric shunt tubing exhibited a statistically significant increase in resistance to flow in 2-piece shunt systems (p<0.05). For 3-piece systems resistance to flow in
Figure 3 Line graphs that display the decrease in resistance to flow as protein concentration increases in both pediatric and adult new catheter systems for 25 cm (Figure 3a), 52 cm (Figure 3b) and 90 cm (Figure 3c) catheter lengths where n=3. Pediatric shunt systems exhibit higher resistance to flow than adult shunt systems. In both systems resistance to flow is shown to decrease as increasing amounts of protein are added. The average resistance to flow measured in Pa·sec/m³ is displayed on the y-axis where E+10 denotes scientific notation \(1.00E+10 = 1.00 \times 10^{10}\) and the concentration of protein added to aCSF is represented on the x-axis in (g/dL).

Figure 4 Line graphs that display the decrease in resistance to flow as protein concentration increases in both pediatric and adult explanted catheter systems for 52 cm (Figure 4a) and 90 cm (Figure 4b) catheter lengths where n=3. In explanted systems there is a slight increase in resistance to flow when comparing pediatric systems to adult systems, although this is not statistically significant. However, increasing concentrations of protein continue to cause a decrease in resistance to flow within explanted adult and pediatric systems. The average resistance to flow measured in Pa·sec/m³ is displayed on the y-axis where E+10 denotes scientific notation \(1.00E+10 = 1.00 \times 10^{10}\) and the concentration of protein added to aCSF is represented on the x-axis in (g/dL).
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Figure 5 Bar graphs depicting the increase in resistance to flow seen between pediatric and adult sized 2-piece (Figure 5a) and 3-piece connector (Figure 5b) systems where n=3. Pediatric 2-piece shunt systems exhibited a statistically significant increase (p<0.05) in average resistance to flow for both 2-piece and 3-piece systems when compared to adult 2-piece and 3-piece systems. The average resistance to flow measured in Pa·sec/m³ is displayed on the y-axis where E+10 denotes scientific notation (1.00E+10 = 1.00 × 10¹⁰).

Table 1 This table displays the combined (adult with pediatric) mean resistance to flow for shunt systems containing zero, one or two connectors. The addition of one and two connectors to adult and pediatric shunts systems when compared to the control (0) caused a statistically significant increase in resistance to flow (p<0.5). However, there was no statistical increase in flow between systems with one or two connectors.

<table>
<thead>
<tr>
<th>Connectors</th>
<th>Mean Resistance to Flow</th>
<th>Std. Error</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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</tr>
<tr>
<td>0</td>
<td>24.57</td>
<td>0.043</td>
<td>23.98 - 25.17</td>
</tr>
<tr>
<td>1</td>
<td>25.313*</td>
<td>0.098</td>
<td>24.98 - 25.65</td>
</tr>
<tr>
<td>2</td>
<td>25.357*</td>
<td>0.106</td>
<td>24.95 - 25.78</td>
</tr>
</tbody>
</table>

*indicates statistical significance (p<0.05) when compared to resistance in control.

The pediatric shunts remained markedly higher than in the adult shunt systems.

DISCUSSION

To date, a solution to the recurring problem of shunt system failure has yet to emerge. Studies show that up to 50% of shunts still fail over time [4,9]. There are a number of factors that can predict shunt lifespan including patient age and number of previous revisions [12,17,18]. While a great deal of research has been done to examine the causes and trends emerging in shunt system failure, more can be learned about the characteristics of flow of CSF through various shunt systems. This project was designed to provide a better understanding of the difference between pediatric and adult CSF shunt systems for both new and explanted shunt systems and using 2-piece systems, 3-piece systems, and with different protein levels.

A majority of the results from our experiments were consistent with the outcomes that would be expected when examining the equations for flow and resistance of Newtonian fluids. According to Pousielle's Law, the flow through a system should increase with a larger radius of shunt tubing and the corresponding resistance to flow should decrease [6]. This was seen when comparing the resistance to flow of adult new catheters with an inner diameter of 1.0 mm versus pediatric new catheters with an inner diameter of 0.7 mm of the same length (Figure 2). This trend continued to be consistent when protein was added to the new catheter shunt systems and with 2-piece, 3-piece systems.

Within a shunt system, flow depends on the pressure across the system and the resistance of the catheters themselves. Normally a shunt system consists of a one-way differential valve and tubing with a fixed resistance. There exists a number of resistors including the catheter and any shunt accessories in a
CSF shunt system. Therefore, the sum of the resistance across a standard shunt system can be represented by the following equation where Rs represents shunt resistance, Rc represents the opening of the ventricular catheter, Rv represents the valve, any shunt accessories (Ra), and finally, the distal tubing (Rt) [19].

\[ R_s = R_v + R_c + R_a + R_t. \]

According to this equation and our previous work examining flow characteristics of CSF shunt systems containing valves and connectors, we expected the resistance to flow in the pediatric systems to increase with the addition of shunt accessories (one and two connectors). It was expected due to the smaller diameter of pediatric catheters that resistance to flow in the pediatric catheter systems containing connectors to be greater than the resistance to flow in adult catheter systems containing connectors. Our data was consistent with both hypotheses.

Our results from the protein experiments in this study were also consistent with our previous work investigating the effects of high protein concentration on the flow of CSF fluid through both new and explanted shunt systems. Previously we tested five different albumin protein concentrations (aCSF, 0.5 g/L, 2 g/L, 5 g/L, 10 g/L) in new and explanted adult shunt systems and found that an increasing protein concentration is associated with a corresponding decrease in mean resistance to flow [14]. Similarly, in this study after the addition of varying albumin concentrations to pediatric shunt systems, a statistically significant (p<0.05) arithmetic decrease in mean resistance to flow was observed.

This experiment represents an initial examination of the consequences of decreasing diameter, increasing protein concentrations, and the addition of shunt accessories on pediatric shunt systems when compared to adult shunt systems. It would be worthwhile to explore how flow through pediatric and adult shunt systems are altered when other components of disease states are added to CSF in high concentrations including erythrocytes, immunoglobulin's, transferrin, and haptoglobin; all of which are suggested to contribute to shunt malfunction [20-22]. Further studies could also be aimed at stimulating in vivo situations by incubating adult and pediatric shunt systems and examining flow of aCSF.

CONCLUSION

There are a variety of similarities and differences between flow through adult and pediatric-sized catheter systems. As the protein concentration within a shunt system increases, the resistance to flow decreases in both adult and pediatric-sized catheters. In addition, a significant increase in resistance to flow was observed in new pediatric-sized catheters when compared to adult sized catheters. Similarly, new pediatric 2-piece and 3-piece catheters exhibited a statistically significant increase (p<0.05) in average resistance to flow compared to adult 2-piece and 3-piece systems. However, for both the adult and pediatric-sized catheters, there was not a statistically significant difference in resistance to flow between new and explanted catheters observed in our laboratory setting. The results suggest important finding that minimum pieces of shunts should be used to decrease chances of blockage. This is the first study to examine the difference in flow dynamics between adult and pediatric-sized catheters across a wide array of experimental conditions.

REFERENCES

