Image-guided cerebrospinal fluid shunting in children: catheter accuracy and shunt survival

Clinical article

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Object. Cerebrospinal fluid shunt placement has a high failure rate, especially in patients with small ventricles. Frameless stereotactic electromagnetic image guidance can assist ventricular catheter placement. The authors studied the effects of image guidance on catheter accuracy and shunt survival in children.

Methods. Pediatric patients who underwent placement or revision of a frontal ventricular CSF shunt were retrospectively evaluated. Catheters were placed using either anatomical landmarks or image guidance. Preoperative ventricular size and postoperative catheter accuracy were quantified. Outcomes of standard and image-guided groups were compared.

Results. Eighty-nine patients underwent 102 shunt surgeries (58 initial, 44 revision). Image guidance was used in the placement of 56 shunts and the standard technique in 46. Shunt failure rates were not significantly different between the standard (22%) and image-guided (25%) techniques (p = 0.21, log-rank test). Ventricular size was significantly smaller in patients in the image-guided group (p < 0.02, Student t-test) and in the surgery revision group (p < 0.01). Small ventricular size did not affect shunt failure rate, even when controlling for shunt insertion technique. Despite smaller average ventricular size, the accuracy of catheter placement was significantly improved with image guidance (p < 0.01). Shunt accuracy did not affect shunt survival.

Conclusions. The use of image guidance improved catheter tip accuracy compared with a standard technique, despite smaller ventricular size. Failure rates were not dependent on shunt insertion technique, but an observed selection bias toward using image guidance for more at-risk catheter placements showed failure rates similar to initial surgeries.

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Key Words • cerebrospinal fluid shunt • hydrocephalus • neuronavigation • frameless stereotaxy • pediatric neurosurgery

Cerebrospinal fluid shunt placement is one of the most commonly performed neurological surgeries in the pediatric population. Despite significant technical advancements, shunts have a high rate of failure, often requiring multiple revision surgeries during the patient’s lifetime. In addition to the health risks, undergoing multiple surgeries represents a significant intellectual burden on the patient17 and an economic burden on society.7,30 Many factors have been evaluated in association with shunt survival, including technique and accuracy of catheter placement,10,14,15,18,33,34,36 surgeon experience,23,28 antibiotic administration,24 catheter and valve type,8,20 patient age,23,28,32 hydrocephalus cause,26,32 and type of revision surgery.19 Nevertheless, operative technique and implanted hardware selection vary widely among experienced neurosurgeons,1 and overall failure rates remain high.13,31

Proximal catheter occlusion is a major cause of shunt failure, and inaccurate proximal catheter placement contributes to obstruction.21,13,18,33 Investigations have attempted to improve proximal catheter placement using imaging and navigation modalities. Despite initial promise,14 endoscopic-assisted shunt placement has not been shown to improve shunt survival in a large prospective study.13 Other types of image guidance in shunt catheter placement that have been
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studied include frameless neuronavigation and electromagnetic guidance. A recent small prospective study of electromagnetic image-guided shunt placement in adults and children showed a substantial reduction of early shunt revision (within 30 days), and the authors concluded that accurate proximal catheter placement improved shunt survival. However, the study criteria excluded patients undergoing shunt revision surgery and those with slit ventricles, and the authors did not measure catheter accuracy. To more comprehensively evaluate the effects of image guidance on catheter accuracy and shunt survival, we undertook a retrospective study of shunt placement that included all children with hydrocephalus undergoing either initial or revision shunt surgery.

Methods

Study Criteria

After approval from the Seattle Children’s Hospital Institutional Review Board, we completed a retrospective radiological and chart review of all pediatric patients (age ≤ 18 years) who underwent surgery for placement or revision of a ventricular CSF shunt at our institution from September 2008 through November 2010. All shunt procedures were performed by attending pediatric neurosurgeons with significant training in image guidance techniques (J.G.O. and S.R.B.).

Inclusion criteria consisted of the placement or replacement of a frontal supratentorial ventricular catheter to treat hydrocephalus of any cause. Patients who underwent shunt revisions that did not include placement of a new ventricular catheter (such as distal or valve revisions), those whose shunts were placed into cavities other than the lateral ventricle (such as the fourth ventricle, nonventricular cysts, or tumor cavities), or patients without available pre- and postoperative imaging were excluded. The study groups were divided by catheter placement technique into an image guidance group and a standard technique group. The image guidance group included all frontal shunts placed with the aid of electromagnetic-assisted frameless stereotaxy (StealthStation AxiEM, Medtronic Navigation, Inc.) as previously described. The standard technique group included those shunts placed via common external landmarks or with the use of the Ghajar Guide (Neurodynamics, Inc.).

Outcome Variables

Initial surgery was defined as the first placement of a ventricular shunt to any distal site (peritoneum or venous system). The conversion of a ventriculostubgaleal reservoir or initial ventriculostomy to a permanent shunt system was also considered an initial surgery if the proximal catheter was replaced. Revision surgery was defined as any subsequent proximal catheter revision for catheter obstruction, new proximal catheter placement into another ventricle, or removal and subsequent replacement of the shunt system. Revisions due to valve failure, distal catheter obstruction, system disconnection, and infection were excluded. Other recorded data included age of the child at ventricular catheter placement and cause of hydrocephalus.

Noncontrast CT scans for each patient were reviewed by a neurosurgeon and 1 of 2 pediatric neuroradiologists (G.E.I. and P.C.K.), who were blinded to the patient name, shunt insertion technique, and patient outcome. The preoperative CT scan was used to determine the degree of ventricular dilation by calculating the frontoorcippital horn ratio. The postoperative CT scan was used to objectively and subjectively grade the ventricular catheter placement; postoperative scans occurred within 12 hours of shunt insertion. Both pre- and postoperative CT scans were obtained with a standardized gantry angle and a slice thickness of 3.75 mm. The objective method was the calculation of the 3D distance from the catheter tip to the foramen of Monro using the following formula:

\[ \text{Accuracy}(3D) = \sqrt{\text{AP}^2 + \text{RL}^2 + \text{CC}^2} \]

where AP is the distance from the catheter tip to the foramen in the anteroposterior direction, RL is the distance in the right-left direction, and CC is the distance in the cranio-caudal dimension. The subjective method used a grading scale describing the environment around the catheter tip developed by Hayhurst et al. The scale has 3 grades: 1) catheter tip floating in CSF equidistant from ventricular walls, away from choroid and a straight trajectory from the bur hole; 2) catheter tip touching ventricle wall or choroid; or 3) part of catheter tip within parenchyma or failure to cannulate the targeted ventricle completely.

Statistical Analysis

Shunt survival time was summarized by Kaplan-Meier survival curves for patient groups and compared by log-rank testing. Covariate analysis was performed using Cox regression analysis. Continuous variables, such as patient demographics and radiological characteristics, were compared with the Student t-test, while categorical variables, such as subjective catheter grading, were compared with Fisher exact tests, as specified in the text. Significance was defined as \( p < 0.05 \).

Results

A total of 89 patients underwent 102 surgeries (58 initial and 44 revision). Image guidance was used in 56 shunts and a standard technique in 46. Baseline patient characteristics and cause of the hydrocephalus are shown in Table 1. There was no significant difference in patient age or hydrocephalus cause between the standard and image guidance groups, but patients undergoing revision surgery were significantly older than those undergoing an initial surgery (8.0 ± 7.0 vs 3.7 ± 5.3 years, \( p < 0.001 \), Student t-test); age at shunt insertion did not affect shunt survival (\( p = 0.76 \), Cox regression). The cause of hydrocephalus also differed between the initial and revision groups (\( p = 0.02 \), Fisher exact test), with more patients with IVH in the revision group and more tumor patients in the initial group. Mean follow-up interval was 7.6 ± 6.0 months (9.7 ± 5.8 months for the standard group and 5.8 ± 5.6 months for the image guidance group; \( p < 0.001 \), Student t-test).

Shunt failure rates due to proximal obstruction were...
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not significantly different between the standard (22%) and image guidance (25%) groups (p = 0.21, log-rank test). There was a trend toward decreased shunt failure in initial surgery when compared with shunt revisions (p = 0.06). In the initial surgery group, 7 (24%) of 29 image-guided shunts failed, compared with 4 (14%) of 29 shunts placed using a standard technique (p = 0.12, Cox regression). Among revisions, 7 (26%) of 27 image-guided shunts failed, compared with 6 (35%) of 17 standard shunts (p = 0.094). There were 3 revisions due to shunt infection, all of which occurred after standard shunt placement and none of which were included in the subsequent analysis of shunt failure.

No significant difference in shunt failure rates was found between hydrocephalus causes, even when comparing subgroups of shunt insertion technique or initial and revision surgeries (data not shown). A specific subgroup analysis of patients with hydrocephalus as the result of previous IVH, historically associated with an increased risk of shunt failure, also showed no significant difference in shunt failure between patients with IVH (4/18, 22%) and those without IVH (20/84, 24%; p = 0.96, log-rank test). The use of image guidance did not significantly change the shunt failure rate among patients with IVH when compared with the standard technique (25% vs 17%, respectively; p = 0.39, Cox regression).

Radiological analysis and catheter accuracy is shown in Tables 2 and 3. Compared with the standard technique, image guidance significantly improved catheter accuracy, measured as the Euclidean distance from the catheter tip to the ipsilateral foramen of Monro (10.17 ± 8.74 mm vs 16.44 ± 10.35 mm; p < 0.01, Student t-test; Table 2). A subgroup analysis showed the improvement in catheter accuracy was significant among initial surgeries (p < 0.001) and a trend in revision surgeries (p = 0.06; Table 3). Ventricular size (as measured by frontooccipital horn ratio) was significantly smaller in patients in the image guidance group (0.49 ± 0.11) compared with the standard technique group (0.56 ± 0.15; p < 0.02; Table 2). A subgroup comparison of those patients undergoing revision surgery demonstrated a trend toward more Grade 1 and 2 catheters in the image guidance group than the standard placement group (p = 0.08, Fisher exact test; Table 3). Shunt survival was not affected by catheter ac-

TABLE 1: Analysis of patient variables according to shunt group and type of surgery

<table>
<thead>
<tr>
<th>Variable</th>
<th>Shunt Insertion Group</th>
<th>Surgery Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard</td>
<td>Image Guidance</td>
</tr>
<tr>
<td>mean age (yrs) ± SD*</td>
<td>5.4 ± 6.5</td>
<td>5.7 ± 6.4</td>
</tr>
<tr>
<td>mean follow-up (mos) ± SD*</td>
<td>9.7 ± 5.8</td>
<td>5.8 ± 5.6</td>
</tr>
<tr>
<td>hydrocephalus cause†</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IVH</td>
<td>6 (13)</td>
<td>12 (21)</td>
</tr>
<tr>
<td>myelomeningocele</td>
<td>10 (22)</td>
<td>12 (21)</td>
</tr>
<tr>
<td>tumor</td>
<td>10 (22)</td>
<td>13 (23)</td>
</tr>
<tr>
<td>aqueductal stenosis</td>
<td>6 (13)</td>
<td>2 (4)</td>
</tr>
<tr>
<td>other‡</td>
<td>14 (30)</td>
<td>17 (30)</td>
</tr>
<tr>
<td>total</td>
<td>46</td>
<td>56</td>
</tr>
</tbody>
</table>

* Comparisons performed using the t-test.
† Data given as number of patients (%); comparisons performed using the Fisher exact test.
‡ Idiopathic, posttraumatic, postinfectious, or no definitive diagnosis.
§ Statistically significant.

TABLE 2: Radiographic analysis of the shunt insertion subgroups

<table>
<thead>
<tr>
<th>Radiographic Variable</th>
<th>Shunt Insertion Group</th>
<th>Surgery Type</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Standard</td>
<td>Image Guidance</td>
</tr>
<tr>
<td>mean accuracy (mm) ± SD*</td>
<td>16.44 ± 10.35</td>
<td>10.17 ± 8.74</td>
</tr>
<tr>
<td>frontooccipital horn ratio</td>
<td>0.56 ± 0.15</td>
<td>0.49 ± 0.11</td>
</tr>
<tr>
<td>catheter grade (%)†</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>21 (46)</td>
<td>27 (48)</td>
</tr>
<tr>
<td>2</td>
<td>16 (35)</td>
<td>24 (43)</td>
</tr>
<tr>
<td>3</td>
<td>9 (19)</td>
<td>5 (9)</td>
</tr>
</tbody>
</table>

* Accuracy defined as the Euclidean distance between the tip of the shunt catheter and the ipsilateral foramen of Monro. Comparisons performed using the Student t-test.
† Comparisons performed using the Fisher exact test.
‡ Statistically significant.
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<table>
<thead>
<tr>
<th>TABLE 3: Radiographic analysis of the surgery type subgroups</th>
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<tbody>
<tr>
<td>Radiographic Variable</td>
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<tr>
<td>------------------------</td>
</tr>
<tr>
<td>mean accuracy (mm) ± SD*</td>
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<tr>
<td>catheter grade (%)†</td>
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<tr>
<td>1</td>
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<tr>
<td>2</td>
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<tr>
<td>3</td>
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</table>

* Comparisons performed using the Student t-test.
† Comparisons performed using the Fisher exact test.
‡ Statistically significant.

accuracy (p = 0.98, log-rank test), ventricular size (p = 0.75), or subjective catheter grade (p = 0.92; data not shown).

Discussion

To our knowledge, this study represents the largest series of children undergoing electromagnetic image-guided shunt placement currently available in the literature and the only such study quantifying catheter accuracy as it relates to image guidance and shunt survival. The use of image guidance significantly improved catheter accuracy as measured on postoperative imaging and showed a trend toward improved subjective appearance of catheter environment, but these variables did not affect shunt survival. Ventricular size was significantly smaller in both image-guided and revision procedures compared with standard and initial surgeries, respectively, suggesting a selection bias toward using image guidance for more difficult catheter placements. Patients undergoing revision surgery showed a trend toward shorter shunt survival.

Although we found no statistically significant improvement in shunt survival using image guidance, several studies, both prospective and retrospective, have demonstrated a reduction in shunt failure rates. Hayhurst et al. showed a 16% reduction in early (< 30 days) proximal catheter failure rates among 34 patients of all ages with image-guided shunt placement compared with 41 patients undergoing standard placement of a shunt. This series did not include revision surgeries or patients with slit ventricles or “abnormal ventricular anatomy” (not defined by the study authors), and it included a small pediatric sample size (15 in the image-guided group and 20 in the standard group). The overall shunt failure rate at 12 months (including from valve dysfunction, infection, and other causes) and overall shunt survival time was not significantly different between the standard and image-guided groups, which is similar to the results in the current study.

A prospective study of pediatric patients by the same group evaluating image-guided shunt placement in 23 children with complex ventricular anatomy (although this characteristic was not quantitatively assessed) noted a proximal failure rate of 9% in 17 months; only initial shunts were studied, and there was no control group. Gil et al. used image guidance in shunt placement in 9 patients with hydrocephalus and small or slit ventricles, 6 of whom were undergoing revisions. No patients required subsequent proximal revisions in the 3- to 13-month follow-up period. Another study of 26 adult patients with slit or dysmorphic ventricles demonstrated “good” catheter placement in 20 of 21 patients with postoperative imaging, although long-term survival was not assessed.

Azzeem and Origitano used image guidance to place initial shunts in 25 patients of a variety of ages and indications, and they found no proximal failures at 1-year follow-up; only 5 patients were children.

Our study did not show an overall survival advantage of shunt placement with image guidance. Importantly, image guidance was more likely to be used in patients with smaller ventricles. Larger ventricles were more likely to be encountered in patients undergoing an initial shunt procedure, and one would intuitively expect accuracy to improve when shunts are placed using a standard technique in this scenario. This may not be the case in revision surgery, especially because ventricular size and shape changes over time after shunt placement.

Tuli et al. studied risk factors for repeated shunt failure and found that young gestational age, cause of hydrocephalus (especially IVH), and a short time interval between revisions were associated with variable increases in risk of shunt failure. Other studies of factors influencing shunt survival found similar increases in shunt failure rates in patients with shorter revision time intervals and hydrocephalus from IVH. In our study, age at shunt insertion was significantly older for revision surgeries, as would be expected for patients who undergo shunt placement at a young age and grow older before requiring revisions; this factor was not associated with shunt failure, although gestational age was not considered. We did not observe a difference in shunt survival between different causes of hydrocephalus (including IVH vs other causes), but the subgroup sizes in our study were small.

A recent investigation by Wan et al. identified which patient factors influenced subjective catheter accuracy (as defined by catheter tip environment) in patients of all ages using standard (freehand) technique. Small preoperative ventricular size (as defined by frontooccipital horn ratio) and younger age were found to negatively affect catheter accuracy. Revision surgeries were not associated with worsened catheter accuracy, although no direct comparison was made between preoperative ventricular size and revision surgery. Survival and failure rates were not considered in this study.
Another study demonstrated worsening shunt survival when the catheter tip was surrounded by brain parenchyma or inserted into slit ventricles. The same study found that larger ventricular size at the time of initial shunting was associated with decreased shunt survival. The authors were unable to account for this conclusion, and our study does not show a significant effect of ventricular size on shunt failure rates, although the number of patients with very small or slitlike ventricles (defined as frontooccipital horn ratio < 0.37) was small (n = 6).

We analyzed only frontal shunts in this study because the ipsilateral foramen of Monro was considered to be a more consistent target compared with parietal or occipital shunts, although the exact target used in the image guidance group was not recorded. Several groups have studied the choice of catheter entry location (frontal, parietal, or occipital) on shunt function and survival, and the data are conflicting. The first major study of shunt entry site and shunt survival found that shunts placed via a frontal bur hole survived significantly longer than parietal shunts. Shortly thereafter, a prospective randomized study of 121 patients undergoing initial shunt insertions compared frontal and parietooccipital entry sites and concluded that parietal shunts survived slightly longer than frontal shunts. Subsequent studies of neonatal, pediatric, and mixed-age patients with shunts have shown no advantage of frontal versus parietal or occipital entry sites.

We observed a significant improvement in catheter tip accuracy in the image guidance group when compared with standard placement, despite significantly smaller preoperative ventricular size. Because the exact coordinate location of the chosen target was not recorded (usually defined as the ipsilateral foramen of Monro, the anterior extent of the choroid plexus), true accuracy of the image guidance system itself cannot be definitively quantified, nor was this the primary focus of this study. Additionally, in patients with very small-sized or abnormal ventricles, alternative targets away from the foramen are occasionally selected if they are of more favorable size and position. While previous laboratory investigations of image guidance systems have shown excellent accuracy, patient studies have indicated an average target localization error of 5.9 ± 4.3 mm. Young patient age was associated with higher navigation system registration error (which may affect targeting accuracy) in previous studies, especially among pediatric patients; only 1 such study qualitatively evaluated postoperative accuracy of a predefined target (foramen of Monro) using image guidance. Our target localization error is likely a combination of young patient age and variable target selection depending on the preoperative size and configuration of the ventricles. Despite these conditions, accuracy was still significantly improved with image guidance when compared with standard placement.

Image guidance in shunt procedures has been criticized for its cost, additional imaging requirements, and increased operating time. We have found the cost of the disposable equipment to be only marginally more expensive than a standard shunt procedure (approximately 2.8% more per operation); the base station is the same as that used in other surgeries requiring image guidance, such as tumor resection. In cooperation with the emergency room and radiology staff, we have developed a protocol wherein fiducials are placed on all patients undergoing CT scanning for suspected shunt malfunction, obviating the need for further scanning for use with image guidance. Finally, in our experience less than 10 minutes was needed to set up and register each patient in the operating room, similar to other groups. Thus, the logistics of image guidance in shunt surgery have minimal impact on the procedural workflow.

This study has several weaknesses. First, because of the retrospective design, we had no control over the shunt placement method; the decision to place a shunt using image guidance or a standard technique was made by the surgeon at the time of operation, and the exact target assigned in image guidance may have varied slightly. While the reasoning behind the choice of placement technique was not available for retrospective analysis, our results suggest a selection bias for the use of image guidance in traditionally at-risk patients more likely to suffer shunt failure, such as those with small ventricular size and those with hydrocephalus from IVH. Second, the sample size, while larger than any previous study of image guidance in pediatric shunt survival, remains small. This small size reduces the power of the study, and any small benefit conferred by image guidance may not have been detected. Third, while the authors attempted to select a time period in which both standard and image-guided techniques were employed across our institution at similar rates, a bias still exists toward slightly longer overall follow-up in patients undergoing standard shunt placement. This likely reflects a steady increase in the use of image guidance over time. Finally, only 1 image guidance system (Medtronic AxiEM) was evaluated, although no similar systems were available in the US at the time of this study. As in other retrospective studies of evolving clinical practice, these differences may prevent the direct comparison between the 2 groups of shunt insertion technique.

Conclusions

We have shown an improvement in ventricular catheter tip accuracy in pediatric CSF shunt insertion when using image guidance, despite smaller average ventricular size. While shunt survival was similar between standard and image-guided groups, a selection bias toward using image guidance for patients with a historically higher risk of shunt failure (such as those with smaller ventricles or hydrocephalus from IVH) was observed. A prospective trial of pediatric shunt technique may account for differences in patient variables and further define the effect of image guidance on shunt survival.

Disclosure

This study was supported in part by an unrestricted educational grant from Medtronic, Inc., to Drs. Levitt and Browd. Author contributions to the study and manuscript preparation include the following: Conception and design: Browd, Levitt, O’Neill, Ojemann. Acquisition of data: Browd, Levitt, O’Neill, Ojemann. Analysis and interpretation of data: Browd, Levitt, Ishak, Khanna, Ojemann. Drafting the article: Levitt. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Browd. Statistical analysis: Levitt, Temkin. Administrative/
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technical/material support: Levitt, Ellenbogen, Ojemann. Study supervision: Browd.

References