Imaging Strategies for Suspected Acute Cranial Shunt Failure: A Cost-Effectiveness Analysis

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abstract

OBJECTIVES: We compared cost-effectiveness of cranial computed tomography (CT), fast sequence magnetic resonance imaging (fsMRI), and ultrasonography measurement of optic nerve sheath diameter (ONSD) for suspected acute shunt failure from the perspective of a health care organization.

METHODS: We modeled 4 diagnostic imaging strategies: (1) CT scan, (2) fsMRI, (3) screening ONSD by using point of care ultrasound (POCUS) first, combined with CT, and (4) screening ONSD by using POCUS first, combined with fsMRI. All patients received an initial plain radiographic shunt series (SS). Short- and long-term costs of radiation-induced cancer were assessed with a Markov model. Effectiveness was measured as quality-adjusted life-years. Utilities and inputs for clinical variables were obtained from published literature. Sensitivity analyses were performed to evaluate the effects of parameter uncertainty.

RESULTS: At a previous probability of shunt failure of 30%, a screening POCUS in patients with a normal SS was the most cost-effective. For children with abnormal SS or ONSD measurement, fsMRI was the preferred option over CT. Performing fsMRI on all patients would cost $27,627 to gain 1 additional quality-adjusted life-year compared with CT. An imaging pathway that involves CT alone was dominated by ONSD and fsMRI because it was more expensive and less effective.

CONCLUSIONS: In children with low pretest probability of cranial shunt failure, an ultrasonographic measurement of ONSD is the preferred initial screening test. fsMRI is the more cost-effective, definitive imaging test when compared with cranial CT.

WHAT’S KNOWN ON THIS SUBJECT: Recently, nonionizing imaging modalities, like rapid MRI and ultrasonographic measurement of optic nerve sheath diameter, have emerged; however, there is a paucity of data on comparative cost-effectiveness versus cranial computed tomography scans for suspected cranial shunt failure.

WHAT THIS STUDY ADDS: For patients with low pretest probability of shunt failure and a normal shunt series (plain radiograph), a screening measurement of optic nerve sheath diameter is the most cost-effective approach. Fast sequence MRI dominated computed tomography alone as the definitive test.

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Ventricular shunts account for ~$1 billion per year in health care costs for hydrocephalus. Emergency department (ED) visits for shunt-related problems are associated with high utilization of imaging resources; 1 pediatric center reported 223 patient visits annually and a median of 2.6 cranial computed tomography (CT) scans per shunt-patient per year.\(^2,3\) Data from the 2009 Kids Inpatient Database of the Health Care Utilization Project suggest that initial shunt placement is responsible for 2519 admissions annually.\(^4\) In a recent prospective multicenter study from 6 pediatric institutions managing 1036 children with shunt placement over a 3-year period, the rate of shunt failure remained high, with 33% having failed within the first year.\(^5\)

Clinical signs and symptoms of shunt failure are nonspecific and clinicians often rely on neuroimaging for diagnosis.\(^2,6–8\) It is estimated that children with cranial shunts receive 1 to 3 CT scans per year as routine surveillance and/or evaluation for shunt failure.\(^2,3,9\) Although CT scans are important for accurate diagnosis of shunt failure, the resulting exposure to ionizing radiation has been linked to long-term risk of malignancy, prompting a search for alternative imaging strategies.\(^10–13\)

In recent years, several promising alternative imaging modalities without the long-term radiation risks have emerged. Fast sequence magnetic resonance imaging (fsMRI) has comparable diagnostic accuracy to CT scans and overcomes the practical limitations of standard MRI by obviating the need for sedation.\(^2,9,14\) Additionally, optic nerve sheath diameter (ONSD) measured by point of care ultrasound (POCUS) may have utility as a rapid bedside screening test for elevated intracranial pressure (ICP). ONSD measurement by ultrasound has been shown to have moderate-to-high sensitivity for detecting shunt failure and high sensitivity for raised ICP with variable specificity.\(^15–19\) It is a reliable and reproducible technique, demonstrating excellent interobserver reliability \((r = 0.89)\).\(^19\)

In a recent meta-analysis and data from neurosurgical literature, ocular sonography has shown to possess high diagnostic accuracy for detecting elevated ICP compared with CT to rule out raised ICP in a low-risk group.\(^15,18–20\)

In contrast, several prospective trials of ocular ultrasound in children with suspected cranial shunt failure reported a much lower sensitivity of 61%.\(^16,17,21\) Although the overall sensitivity of ONSD in detecting elevated ICP is modest, the high negative predictive value of this noninvasive point of care test supports its use as a screening tool, which may help identify patients with suspected shunt malfunction for whom an advanced imaging test like CT or MRI is not warranted.\(^20,21\)

With respect to the time course of development and resolution of changes in ONSD, a study of isolated human optic nerves has shown ONSD changes within minutes of pressure changes induced by intrathecal infusion, making its measurement a potentially accurate real time reflection of ICP.\(^22\) Two case reports have also described a rapid reduction in ONSD after a therapeutic lumbar puncture for idiopathic intracranial hypertension.\(^23,24\)

For patients with cranial shunt for hydrocephalus, it has been suggested that baseline values for ONSD be determined during interval surveillance visits because children with shunt physiology may have measurements that are higher than normative values previously reported in the literature.\(^25\) This would decrease likelihood of false-positive measurements in this population. Given the emergence of fsMRI and ONSD measurement and uncertainty around the tradeoff between risks and benefits of CT, there is a need to determine if an optimal cost-effective imaging approach exists. Our aim for this study was to compare the cost-effectiveness of the available imaging strategies for suspected shunt failure. In particular, we examined 4 strategies: (1) CT scan, (2) fsMRI, (3) screening POCUS combined with CT, and (4) screening POCUS combined with MRI.

**METHODS**

**Study Design**

We performed a cost-effectiveness analysis of 4 imaging strategies for suspected cranial shunt malfunction by using TreeAge Pro 2014 (TreeAge Software Inc, Williamstown, MA) following published guidelines and the consolidated health economic evaluation reporting standards.\(^26\) Imaging options were compared by incremental cost-effectiveness ratios (ICERs) and net monetary benefit (NMB). This study was based on literature review and exempt from review by our institutional review board.

**Population and Imaging Strategies**

For pediatric patients (age <18 years) in the ED with signs and/or symptoms of suspected cranial shunt malfunction, we examined the 4 abovementioned imaging strategies. All patients received an initial plain radiographic shunt series (SS). For the pathway incorporating POCUS as a screening test, if the result of the initial SS was positive, patients proceeded to a definitive imaging study (fsMRI or CT) without POCUS. If the result of the initial SS was negative, patients received a POCUS examination. If the result of the POCUS examination was positive, a CT scan or fsMRI was performed. If the result of the POCUS examination was negative, patients were modeled as though they were discharged (Fig 1 A and B).
FIGURE 1
A and B, Decision analysis tree using 3 strategies for a hypothetical population of patients <19 years old with suspected shunt malfunction: CT, fMRI, and POCUS, each depicted as square decision nodes. After the initial choice, an outcome is observed of chance events (circles). Each branch ends at a possible terminal node (triangles). Utilities are listed at each terminal node. fMRI, fast sequence magnetic resonance imaging.
Clinical Data and Cost Inputs

Clinical Inputs

Model inputs used standard definitions and data from recently published studies (Table 1). The patient in the base case was a previously healthy 2-year-old with normal life expectancy (78 years) based on the average age of neuroradiology surveillance commencement with shunted hydrocephalus.9 Furthermore, the risk of radiation-induced carcinogenesis is highest and most relevant for young patients.27 Pretest probabilities were estimated for a symptomatic, at-risk population.26,7,28,29 Probability of shunt failure was found to be 30% based on a quality improvement study evaluating a pathway used by providers at a tertiary care pediatric ED with 85,000 patient visits per year, which is similar to our own institution.2,30 To define the test characteristics of imaging modalities, we used a weighted average from published data that evaluated the test characteristics of the SS, CT, POCUS, and fsMRI. Age-specific mortality for the general population was taken from the US life expectancy tables.31

Costs

Short-term hospital costs of care were derived from the Pediatric Health Information System (PHIS), a deidentified administrative database maintained by the Children’s Hospital Association (Overland Park, Kansas), a consortium of 48 US not-for-profit tertiary care children’s hospitals. The PHIS includes administrative and billing data on inpatient, ED, ambulatory surgery, and observation discharges for the purpose of external benchmarking. Data quality and reliability are assured through the Children’s Hospital Association and participating hospitals and are subjected to a number of reliability and validity checks before being included in the database. Billed hospital charges were converted to costs by use of the hospital, year, and service-specific ratios of cost-to-charge obtained through the Medicare cost report system database and are adjusted for regional cost of living with the Medicare cost report system (Table 2). The 39 hospitals that provided data to PHIS throughout the entire study period in 2015 were included in this study.

Professional fees were included in each imaging pathway and calculated by using national 2015 Medicare physician fee schedule payments associated with appropriate Current Procedural Terminology (CPT) codes. We did not include professional fees for a limited ocular ultrasound because recent data from the Medicare population suggest there are no emergency physicians in the United States that are billing separately for this service.41 Anesthesia fees were based on a mean of 60 minutes for the shunt repair procedure.41 Hospital facility fees for outpatient limited ocular ultrasonography and a level 5 ED visit were obtained from the 2015 Medicare outpatient prospective payment system national payment rates.42 The facility cost of POCUS listed in Table 2 was $93.68.

The total cost of management of future radiation-induced malignancy from a single current generation cranial CT was derived from the literature.40 All micro costs and ranges used for sensitivity analysis are shown in Table 2.

Utilities

Utilities are a numeric measure representative of the quality of life of an individual with a particular state of health (ie, represents a patient with a malignancy or cranial shunt failure) (Table 3). They represent the strength of an individual’s preference for different health states. In our model, we assigned values (or utilities) to health outcomes using a standard Health Utilities Index scale ranging from 0 (death) to 1 (baseline health, assumed as perfect health for this hypothetical population). The Health Utilities Index is a 15-item questionnaire designed to ask the minimum number of questions required to classify a subject’s

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**Table 1 Input Probabilities**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base Case Analysis</th>
<th>Range for Sensitivity Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pretest probability of shunt failure2</td>
<td>30%</td>
<td>10%–50%</td>
</tr>
<tr>
<td>Sensitivity of CT22–37</td>
<td>66%</td>
<td>53%–88%</td>
</tr>
<tr>
<td>Specificity of CT22–37</td>
<td>87%</td>
<td>76%–96%</td>
</tr>
<tr>
<td>Sensitivity of fsMRI22–38</td>
<td>58%</td>
<td>51%–78%</td>
</tr>
<tr>
<td>Specificity of fsMRI22–38</td>
<td>93%</td>
<td>89%–98%</td>
</tr>
<tr>
<td>Sensitivity of ONSD16–19</td>
<td>75%</td>
<td>61%–83%</td>
</tr>
<tr>
<td>Specificity of ONSD16–19</td>
<td>32%</td>
<td>22%–38%</td>
</tr>
<tr>
<td>Sensitivity of SS35–37</td>
<td>19%</td>
<td>4%–30%</td>
</tr>
<tr>
<td>Specificity of SS35–37</td>
<td>95%</td>
<td>91%–98%</td>
</tr>
<tr>
<td>Probability of death and/or missed diagnosis4</td>
<td>0.1% (1:1000)</td>
<td>0.01%–0.2%</td>
</tr>
<tr>
<td>Probability of radiation-induced malignancy26,21,31,39</td>
<td>0.22%</td>
<td>0.07%–0.6%</td>
</tr>
</tbody>
</table>

Patient metrics

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>No. of cranial CTs per patient-year2,9</td>
<td>1</td>
</tr>
<tr>
<td>Age</td>
<td>1</td>
</tr>
<tr>
<td>Life expectancy24</td>
<td>78</td>
</tr>
<tr>
<td>Average annual mortality rate from cancer21</td>
<td>5%</td>
</tr>
<tr>
<td>Length of headache/delayed diagnosis, wk4</td>
<td>1</td>
</tr>
<tr>
<td>Postoperative recovery time, wk4</td>
<td>4</td>
</tr>
<tr>
<td>Discount rate41</td>
<td>3%</td>
</tr>
</tbody>
</table>

Parameter Base Case Analysis | Range for Sensitivity Analysis
Pretest probability of shunt failure2 | 30% | 10%–50% |
Sensitivity of CT22–37 | 66% | 53%–88% |
Specificity of CT22–37 | 87% | 76%–96% |
Sensitivity of fsMRI22–38 | 58% | 51%–78% |
Specificity of fsMRI22–38 | 93% | 89%–98% |
Sensitivity of ONSD16–19 | 75% | 61%–83% |
Specificity of ONSD16–19 | 32% | 22%–38% |
Sensitivity of SS35–37 | 19% | 4%–30% |
Specificity of SS35–37 | 95% | 91%–98% |
Probability of death and/or missed diagnosis4 | 0.1% (1:1000) | 0.01%–0.2% |
Probability of radiation-induced malignancy26,21,31,39 | 0.22% | 0.07%–0.6% |

Patient metrics

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<td>Length of headache/delayed diagnosis, wk4</td>
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<td>Postoperative recovery time, wk4</td>
<td>4</td>
</tr>
<tr>
<td>Discount rate41</td>
<td>3%</td>
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</tbody>
</table>
health status. Parents complete the Health Utilities Index; from responses to this questionnaire, one can derive a multi-attribute utility function. Scores range from death (0) to full health (1.00). The Health Utilities Index has been shown to have reasonable interrater reliability and has previously been applied to a number of other pediatric disease states.43,44 In a study comparing published cost utility analyses for pediatric health states obtained by recommended utility assessment methods (ie, time trade-off, standard gamble) in 4016 parent interviews, the Health Utilities Index for mild-to-severe intellectual disability ranged from 0.59 to 0.83 and moderate-to-severe cerebral palsy from 0.60 to 0.76.43

Our utilities are also consistent with data from other chronic disease states, like asthma, seizure disorder, and static encephalopathy.53 The mean score of the Health Utilities Index for survivors of a cardiac salvage extracorporeal membrane oxygenation (ECMO) program was 0.75 ± 0.19 (range, 0.41–1.0).54 With delayed diagnosis of shunt failure, we assigned a utility of 0.7 extrapolated from literature on patients with migraine headaches.55 Because of a lack of data regarding utility estimates for operative assessment of shunt failure, we considered operative evaluation for shunt failure clinically equivalent to undergoing a prompt neurosurgical intervention for a clinically important traumatic brain injury, assigning a baseline utility of 0.95.27,56

To address the variation in assessment of health care utilities, we included a broad range of 0.5 to 1 within our sensitivity analysis.

### TABLE 2 Key Micro Costs: 2015 CMS and Hospital Cost Data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0222 (APR DRG for ventricular shunt surgery)</td>
<td>0–2 d</td>
<td>10,231.82</td>
<td>6115–58,404</td>
</tr>
<tr>
<td>CT brain</td>
<td></td>
<td>2024</td>
<td>518–52,57</td>
</tr>
<tr>
<td>MRI</td>
<td></td>
<td>3239</td>
<td>1008–8,641</td>
</tr>
<tr>
<td>Facility charge (2015 Medicare payment)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 5 ED visit (APC 0816)</td>
<td></td>
<td>493</td>
<td>394–592</td>
</tr>
<tr>
<td>Ocular ultrasound (limited), CPT 75612</td>
<td></td>
<td>93.68</td>
<td>74.94–112.42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description of service</th>
<th>CPT code</th>
<th>Total RVUs</th>
<th>Professional fee&lt;sup&gt;a&lt;/sup&gt; (range ± 20%), US $</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 5 ED visit (high complexity)</td>
<td>99,285</td>
<td>4.83</td>
<td>176</td>
</tr>
<tr>
<td>Observation/hospitalization (same date)</td>
<td>99,236</td>
<td>6.12</td>
<td>219</td>
</tr>
<tr>
<td>Initial hospital care</td>
<td>99,223</td>
<td>5.7</td>
<td>204</td>
</tr>
<tr>
<td>Subsequent hospital care</td>
<td>99,233</td>
<td>2.91</td>
<td>104</td>
</tr>
<tr>
<td>Discharge from hospital care</td>
<td>99,239</td>
<td>3</td>
<td>107</td>
</tr>
<tr>
<td>Replace and/or revise brain shunt</td>
<td>62,230</td>
<td>24.09</td>
<td>861</td>
</tr>
<tr>
<td>Replace and/or irrigate catheter</td>
<td>62,225</td>
<td>14.93</td>
<td>534</td>
</tr>
<tr>
<td>CSF shunt reprogram</td>
<td>62,232</td>
<td>2.41</td>
<td>86</td>
</tr>
<tr>
<td>CT brain without contrast</td>
<td>70,450</td>
<td>3.49</td>
<td>125</td>
</tr>
<tr>
<td>MRI brain without contrast</td>
<td>70,557</td>
<td>4.87</td>
<td>178</td>
</tr>
<tr>
<td>Anesthesia surgery on brain (base)</td>
<td>6 U</td>
<td></td>
<td>136</td>
</tr>
<tr>
<td>Anesthesia (15–60 min)</td>
<td>4 U</td>
<td></td>
<td>90</td>
</tr>
<tr>
<td>Total anesthesia billing</td>
<td>10 U</td>
<td></td>
<td>226</td>
</tr>
<tr>
<td>Total cost of management of future radiation-induced cancer&lt;sup&gt;21,27&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> On the basis of the 2015 Medicare conversion factor of 35.7547 and anesthesia conversion factor of 22.6093.

### TABLE 3 Utility Estimates

<table>
<thead>
<tr>
<th>Utilities</th>
<th>Base Case Analysis</th>
<th>Range for Sensitivity Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline state of health&lt;sup&gt;45–49&lt;/sup&gt;</td>
<td>1</td>
<td>0.9–1</td>
</tr>
<tr>
<td>Cranial shunt repair&lt;sup&gt;40,51&lt;/sup&gt; (disutility for 30 d postoperative recovery)</td>
<td>0.85</td>
<td>0.5–1</td>
</tr>
<tr>
<td>Delayed diagnosis (continued symptoms)&lt;sup&gt;30,52&lt;/sup&gt;</td>
<td>0.7</td>
<td>0.5–1</td>
</tr>
<tr>
<td>Radiation-induced brain cancer&lt;sup&gt;21&lt;/sup&gt;</td>
<td>0.79</td>
<td>0.5–1</td>
</tr>
</tbody>
</table>
Model Structure

In our decision analysis, we included a plain radiographic study (SS) for all patients with suspected shunt failure. The SS is a low-risk, highly specific test that is used to assess disconnection or breakage of shunt tubing. For a symptomatic patient presenting to the ED, if the SS was abnormal, we assumed the patient would require definitive cranial imaging (CT or MRI) and admission for revision of shunt tubing. This is the practice at our institution and consistent with current pediatric neurosurgical practice at most tertiary pediatric facilities (personal communication).

Our model defined shunt failure as intraoperative findings of malfunction. Nonsurgical interventions, such as shunt valve-adjustment, were excluded. We did not differentiate between shunt malfunction resulting in neurologic deficits and those with clinically insignificant findings. We also assumed all patients with CT or fMRI findings suggestive of shunt failure had operative evaluation.

The primary node of the decision tree represents the choice of CT, fMRI, or screening initially with POCUS. Within the POCUS arm of the model, there is a downstream decision node regarding the use of CT or fMRI. The model simulated the course of events, starting from the initial diagnostic imaging test at age 2 years and ending when the patient died or reached their expected life expectancy. During the simulation, there were 4 possible health states in which the child could exist: shunt failure, radiation-induced head and/or neck cancer, healthy, or dead. Additional branch points within the model represent the probability of certain events occurring (chance nodes) and the transition between these several states with continuing risk over time (Markov nodes). Terminal nodes within the model represent outcomes and were assigned values or “payoff” based on quality-adjusted life-years (QALYs) and costs. A discount rate of 3% was applied to calculate discounted QALYs and costs in accordance with standard recommendations and previous studies.34,57,58

The missed diagnosis or accuracy of the 3 radiologic tests is captured in the model as the proportion of false-negatives (1-sensitivity) and false-positives (1-specificity) of the 4 imaging strategies. In the base case, if the imaging test is falsely interpreted as being normal or unchanged from previous visits, we assumed that the child would have persistent symptoms for a week, return, and have their shunt repaired. We also incorporated a small yet finite risk of mortality (1:1000) when a patient is discharged from the ED with a missed diagnosis. The literature on return visits for recurrent symptoms in pediatric patients with a cranial shunt is scant. Moreover, there is wide variation in clinical presentation of children that return after an initial visit during which shunt failure was missed. Because these patients usually warrant hospitalization, any additional imaging tests (if performed or indicated) would be included in the global cost of inpatient services for a patient with shunt failure.

Statistical Analysis

Outcomes

The 4 imaging strategies were compared in terms of QALYs, total lifetime costs, ICERs, and NMB. We used willingness to pay (WTP) thresholds of both $50,000 and $100,000 per QALY, as suggested by Drummond et al,59 and assessed cost-effectiveness from the perspective of a health care organization.38 The statistical uncertainty of our results was estimated by calculating 95% bootstrap confidence intervals.

Sensitivity Analysis

Sensitivity analyses were performed to determine how key assumptions regarding clinical inputs and cost parameters influenced base case results. One-way sensitivity analyses were represented with a tornado diagram, which demonstrates how our base case estimates for ICERs would change as a single parameter is varied. A probabilistic sensitivity analysis was conducted by using Monte Carlo simulation to simultaneously assess uncertainty around all key parameters. We performed 50,000 second-order simulations with probabilities, outcomes, and costs drawn from plausible distributions. Probabilities followed β distributions, whereas other parameter distributions were assumed to be triangular and bounded by upper and lower parameter estimates. Results from the Monte Carlo simulations were assessed with cost-effectiveness acceptability curves and ICER plots.

RESULTS

In the base case analysis, the 2-step approach of POCUS followed by fMRI (ie, POCUS-fMRI) was the most cost-effective strategy as determined by NMB (WTP = $100,000) (Table 4). The incremental cost per additional QALY gained for this strategy compared with POCUS-CT was $30,289. The ICER for fMRI versus POCUS followed by CT (ie, POCUS-CT) was $66,654. Separate from the 4 strategies, we also evaluated a POCUS only option. Performing fMRI on all patients would cost $269,770 to gain 1 additional QALY compared with a POCUS only strategy.

Probability of radiation-induced cancer, cancer mortality rate, and specificity of the CT scan were significant contributors to model uncertainty. Table 5 shows the threshold values for key variables when the model favors an alternate imaging strategy. Additional one-way
sensitivity analyses comparing POCUS-CT, CT, and fsMRI also demonstrated dependence on these parameters.

An ICER plot of the Monte Carlo simulation is demonstrated in Fig 2. In the probabilistic sensitivity analysis, the median difference in NMB (POCUS-fsMRI versus POCUS-CT) at WTP threshold of $50 000 per QALY was $1141 (interquartile range $565–$1979) per QALY per patient in favor of performing ultrasound, and $2781 (interquartile range $1496–$4546) per QALY at a WTP threshold of $100 000. At a WTP threshold of $50 000 per QALY, POCUS-fsMRI was the optimal strategy 93% of the time and 78% of the time at a WTP threshold of $100 000 per QALY (Fig 3).

**DISCUSSION**

Our aim for this study was to provide guidance to frontline clinicians who must decide on an initial testing strategy for shunt failure evaluation. In the base case and probabilistic sensitivity analysis, POCUS-fsMRI was the most effective strategy. Sensitivity analysis indicates, however, that a POCUS-fsMRI being the optimal strategy depends on parameter estimates of risks associated with cancer, pretest probability of shunt failure, CT test characteristics, and the WTP threshold. We are not aware of any previous literature describing a comparative cost-effectiveness analysis of imaging strategies for suspected cranial shunt failure in a pediatric patient.

Our model suggests that an ultrasonographic assessment of ONSD, contingent on results of plain radiography (SS), is the most cost-effective diagnostic strategy. A screening emergency physician-directed ultrasound informs decision-making for the patient with suspected shunt malfunction. Ultrasonography may be particularly beneficial if it decreases utilization of advanced imaging tests like fsMRI or CT in children with ventricular shunts who are likely to experience multiple rounds of imaging during the course of a lifetime.

Notably, our cost-effectiveness analysis incorporates a conservative measure of the benefit of an ultrasound because of low sensitivity test characteristics of the studies contained within the analysis. It is likely that the ICER of performing POCUS would be greater based on a recent meta-analysis showing much higher diagnostic accuracy.15,19,60 However, we should note that although ultrasound, CT, and MRI are important in the workup of a patient with possible shunt malfunction, imaging alone does not surpass the physician’s clinical assessment (including fundoscopic examination), experience, and judgment. The history and examination assess pretest probability of shunt malfunction and determine the urgency of surgery, whereas imaging remains the most critical additional piece of information in neurosurgical decision-making.

We recognize that many institutions may not have the training or expertise in POCUS. From a screening perspective, an initial approach incorporating a sensitive instead of a specific test makes logical sense, but it requires a shift in practice patterns. In such instances, fsMRI

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**TABLE 4** Base Case Estimates of Cost-Effectiveness Analysis

<table>
<thead>
<tr>
<th>Diagnostic Strategy</th>
<th>Cost, US $</th>
<th>Incremental Cost, US $</th>
<th>Effectiveness, QALY</th>
<th>Incremental Effectiveness</th>
<th>ICER, a US $</th>
<th>Δ NMB (WTP 100 000), a US $</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT</td>
<td>7664.26</td>
<td>7664.26</td>
<td>30.6349</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>POCUS-CT</td>
<td>6880.82</td>
<td>—883.45</td>
<td>30.6435</td>
<td>0.0096</td>
<td>—79 108.6</td>
<td>1547.38</td>
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<tr>
<td>MRI</td>
<td>8553.85</td>
<td>989.59</td>
<td>30.6671</td>
<td>0.0322</td>
<td>27 627.0</td>
<td>2330.33</td>
</tr>
<tr>
<td>POCUS-fsMRI</td>
<td>7710.03</td>
<td>46.57</td>
<td>30.6676</td>
<td>0.0327</td>
<td>1424.2</td>
<td>3225.71</td>
</tr>
</tbody>
</table>

—, not applicable.

* Values for strategies obtained by comparison with CT.

**TABLE 5** Threshold Analysis for Imaging Strategies for Evaluation of Suspected Shunt Failure

<table>
<thead>
<tr>
<th>Baseline</th>
<th>Comparator</th>
<th>Variable</th>
<th>Threshold, WTP 50 000</th>
<th>Threshold, WTP 100 000</th>
</tr>
</thead>
<tbody>
<tr>
<td>POCUS-fsMRI</td>
<td>POCUS-CT</td>
<td>Probability of CA</td>
<td>0.00124</td>
<td>—</td>
</tr>
<tr>
<td>POCUS-fsMRI</td>
<td>POCUS-CT</td>
<td>CT specificity</td>
<td>0.937</td>
<td>—</td>
</tr>
<tr>
<td>POCUS-fsMRI</td>
<td>POCUS-CT</td>
<td>Mortality rate of CA</td>
<td>0.011</td>
<td>—</td>
</tr>
<tr>
<td>POCUS-fsMRI</td>
<td>MRI</td>
<td>Probability of death from shunt failure</td>
<td>—</td>
<td>0.0093</td>
</tr>
<tr>
<td>POCUS-CT</td>
<td>MRI</td>
<td>Probability of CA</td>
<td>0.00261</td>
<td>0.00132</td>
</tr>
<tr>
<td>POCUS-CT</td>
<td>MRI</td>
<td>CT specificity</td>
<td>0.811</td>
<td>0.956</td>
</tr>
<tr>
<td>POCUS-CT</td>
<td>MRI</td>
<td>Mortality rate of CA</td>
<td>—</td>
<td>0.015</td>
</tr>
<tr>
<td>POCUS-CT</td>
<td>CT</td>
<td>Probability of death from shunt failure</td>
<td>—</td>
<td>0.0095</td>
</tr>
<tr>
<td>MRI</td>
<td>CT</td>
<td>Probability of CA</td>
<td>0.00094</td>
<td>—</td>
</tr>
<tr>
<td>MRI</td>
<td>CT</td>
<td>CT specificity</td>
<td>0.940</td>
<td>—</td>
</tr>
</tbody>
</table>

In paired comparisons, baseline strategy is optimal strategy. CA, cancer. —, not applicable.
a careful clinical examination with bedside ocular ultrasonography, if available, in conjunction with neurosurgical consultation may be all that is necessary.

There are several limitations to this study. First, radiation risk is variable according to institution, age, sex, body size, scanner type, and radiation dose. However, sensitivity analyses allowed us to vary radiation risks, accounting for both the inaccuracies of estimates and individualization of these variations. Second, the model is limited by the decision to include only factors that contribute directly to patient outcomes, without consideration of societal implications. Third, the literature used to generate probabilities is heterogeneous and includes multiple etiologies of

FIGURE 2
ICER plot of imaging strategies. The CT-only strategy represents the baseline for comparison. Data were generated from 50,000 second-order simulations by using Monte Carlo simulation. Ovals around the data represent the boundary of an area encompassing 95% of data for a particular imaging strategy. WTP is plotted at both $50,000 and $100,000 per QALY.

would be the preferred initial option. If institutional constraints limit the availability of 24/7 MRI, a cranial CT would then be the preferred initial imaging test.

There continues to be a misunderstanding about radiation and medical imaging among both public and health care providers. Moreover, a recent systematic literature review suggests there is minimal sharing of information before nonacute imaging studies between patients and physicians about potential long-term radiation risks.

Although the true risk of radiation is debated and controversial, several recent studies continue to show an association between increased lifetime risk of cancer and radiation exposure. The disputed evidence from the original Pearce et al study was recently addressed in a revised article by the same group that showed a subsequent risk of leukemia and brain tumors even after assessment of an underlying contributing comorbidity. Limited cranial CT scan techniques to decrease exposure in patients with a ventriculoperitoneal shunt have also been recently proposed. Therefore, in our model, rather than eliminate the risk entirely, we decreased the risk of radiation-induced cancer to 7 per 10,000 as the lower limit in our sensitivity analysis.

Selecting an optimal imaging strategy is best made by shared decision-making with the child’s caregivers about anticipated radiation doses, long-term risk of malignancy from ionizing radiation, and test costs. In a child with low probability of shunt malfunction, an imaging strategy with the lowest risk of long-term radiation exposure is recommended. In a child with high probability of shunt malfunction, a cranial CT would be the preferred initial imaging test.

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shunt failure and utilizes variable definitions of shunt malfunction. However, sensitivity analysis provides insight on how varying model inputs, such as pretest probability, can affect optimal imaging strategy. Fourth, we may have unintentionally assigned lower utilities to health status associated with shunt malfunction. However, our utilities are consistent with data from other chronic disease states, like asthma, seizure disorders, and static encephalopathy.43 For example, a study comparing published cost utility analyses recommends that the Health Utilities Index for mild-to-severe intellectual disability range 0.59 to 0.83 and that the Health Utilities Index for moderate-to-severe cerebral palsy range 0.60 to 0.76.43 We also assumed that these measurements are fixed over time; sensitivity analyses would attenuate this limitation.

We did not include a shunt tap in our model. In our institutional experience, it is infrequently performed because of the risk of introducing infection and because it frequently yields equivocal results. The procedure is generally reserved for children with high pretest probability of shunt malfunction without an interval change in their imaging studies. In addition, the majority of these patients are observed, independent of the results of the shunt tap, and either admitted and/or undergo a shunt revision. Hence, the cost associated with this procedure is included in the cumulative inpatient costs of pediatric patient management with a shunt. A reason not to perform a shunt tap, despite persistent symptoms, may be a child with slit ventricle syndrome. Ultimately, clinical judgment of the attending neurosurgeon determines role of a shunt tap.

The focus of our model is the pediatric patient with low-to-intermediate probability of shunt failure. Therefore, rather than include a shunt tap as a separate decision node, we elected to vary the pretest probability from 10% to 50% in our sensitivity analysis.

There is a paucity of literature regarding recurrence of symptoms in children with cranial shunts. Although recurrence of new symptoms will occur over time, their frequency and specific association with shunt failure is variable. Over the course of the patient’s lifetime, the greater the frequency of recurrences, the higher the potential for receiving CT imaging at each clinical encounter. However, the exact relationship between cumulative independent exposures to ionizing radiation and lifetime risk of radiation-induced carcinogenesis is unclear.

With the availability of advanced neuroimaging tests, the value of the SS is debated. At all of our

**FIGURE 3**

Cost-effectiveness acceptability curve at various WTP thresholds. A cost-effective acceptability curve represents the percentage of iterations within the probabilistic sensitivity analysis (y-axis) plotted against the WTP threshold set at increasing values (x-axis). The WTP represents how much money a society is willing to pay for an increase in 1 QALY. The above graph demonstrates the cost-effectiveness acceptability curves for all 4 strategies.
institutions, a SS is routinely performed because of its high specificity, relatively low cost, and extremely low risk of radiation exposure. Hence, in our model all patients received a SS first.

If a patient with a normal screening ONSD was discharged from the hospital, at worst we assumed morbidity to entail persistent symptoms or headache and assigned a disutility of 0.3 over a week. Because the literature on mortality in missed shunt malfunction is sparse, we assumed this rate to be a conservative estimate of 1 per 100,000. It may be acceptable to discharge a patient with low probability (ie, false-negative ONSD) of shunt failure because the condition will eventually be diagnosed if patients have a good understanding of the need to return for persistent or worsening symptoms.

With respect to normative data in pediatrics, it is important to establish baseline ONSDs for a symptomatic child with cranial shunts because they have a higher baseline ONSD. Access to these baseline measurements, much like a review of previous CT or fsMRI for ventricular size, would enhance the accuracy of an emergency physician-performed POCUS.

Rapid sequence MRIs have some limitations. Compared with CT, they are not as reliable at assessing the positions of ventricular catheter, small intracranial hemorrhage, or pneumocephalus in a shunt malfunction setting. However, in 1 recent study, albeit underpowered, the accuracy and specificity of rapid cranial MRI was not inferior to CT (within an a priori noninferiority margin of 10%).

In addition, programmable ventricular devices require additional time and resources to reset the shunt after an MRI scan. The 2015 Medicare professional fee for programming a shunt (Table 2) was $86. We did not include this cost in our model for 2 reasons: not all shunts placed in pediatric patients are of the programmable type and, compared with the median cost of an MRI ($3239), the cost of reprogramming a shunt is relatively small. Therefore, even in the scenario of all shunt valves being programmable, we believe that this small additional cost is incorporated within the range of costs of an MRI scan in our sensitivity analysis ($1008–$8641).

In terms of cost, MRIs are generally more expensive than CT scans. As the American Medical Association’s CPT does not specify codes to bill for professional and technical services for a limited MRI study such as this, the charges submitted by the hospital tend to be higher than a CT. However, on the basis of recent data from similar pediatric institutions, the marginal cost and charges for a rapid cranial MRI may not be significantly greater than a CT scan.

Finally, potential delays in care related to emergency access to fsMRI, as well as need for sedation should be examined on an institutional basis. With current fast image acquisition protocols, times ranging from 1 to 4 minutes for a T2-weighted rapid MRI scan are comparable to 2 minutes for a CT scan with reduced motion artifact.

CONCLUSIONS

The routine use of CT for cranial shunt malfunction may cause more long-term harm than benefit because of the excess lifetime risk of radiation-induced malignancy. If the pretest probability is low, our model highlights a screening bedside ultrasonographic measurement of ONSD followed by fsMRI to be the most cost-effective. In EDs in which bedside ultrasonography expertise is unavailable, fsMRI is the next best option.

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ABBREVIATIONS

CT: computed tomography
ED: emergency department
fsMRI: fast sequence magnetic resonance imaging
ICER: incremental cost-effectiveness ratio
ICP: intracranial pressure
NMB: net monetary benefit
ONSD: optic nerve sheath diameter
PHIS: Pediatric Health Information System
POCUS: point of care ultrasound
QALY: quality-adjusted life-year
SS: shunt series
WTP: willingness to pay
REFERENCES


24. Singleton J, Dagan A, Edlow JA, Hoffmann B. Real-time optic nerve...


54. Mahle WT, Forbess JM, Kirshbom PM, Cuadrado AR, Simsic JM, Kanter KR. Cost-utility analysis of salvage cardiac extracorporeal membrane oxygenation


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