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(Continued on next page)

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Diagnostic Accuracy of Non-Invasive Thermal Evaluation of Ventriculoperitoneal Shunt Flow in Shunt Malfunction: A Prospective, Multi-Site, Operator-Blinded Study

BACKGROUND: Thermal flow evaluation (TFE) is a non-invasive method to assess ventriculoperitoneal shunt function. Flow detected by TFE is a negative predictor of the need for revision surgery. Further optimization of testing protocols, evaluation in multiple centers, and integration with clinical and imaging impressions prompted the current study.

OBJECTIVE: To compare the diagnostic accuracy of 2 TFE protocols, with micropumper (TFE+MP) or without (TFE-only), to neuro-imaging in patients emergently presenting with symptoms concerning for shunt malfunction.

METHODS: We performed a prospective multicenter operator-blinded trial of a consecutive series of patients who underwent evaluation for shunt malfunction. TFE was performed, and preimaging clinician impressions and imaging results were recorded. The primary outcome was shunt obstruction requiring neurosurgical revision within 7 d. Non-inferiority of the sensitivity of TFE vs neuro-imaging for detecting shunt obstruction was tested using a prospectively determined a priori margin of -2.5% .

RESULTS: We enrolled 406 patients at 10 centers. Of these, 68/348 (20%) evaluated with TFE+MP and 30/215 (14%) with TFE-only had shunt obstruction. The sensitivity for detecting obstruction was 100% (95% CI: 88%-100%) for TFE-only, 90% (95% CI: 80%-96%) for TFE+MP, 76% (95% CI: 65%-86%) for imaging in TFE+MP cohort, and 77% (95% CI: 58%-90%) for imaging in the TFE-only cohort. Difference in sensitivities between TFE methods and imaging did not exceed the non-inferiority margin.

CONCLUSION: TFE is non-inferior to imaging in ruling out shunt malfunction and may help avoid imaging and other steps. For this purpose, TFE only is favored over TFE+MP.

KEY WORDS: Cerebrospinal fluid, Hydrocephalus, Ventriculoperitoneal shunt, Ventriculoperitoneal shunt flow, Ventriculoperitoneal shunt malfunction

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Current diagnostic techniques used for evaluating ventriculoperitoneal shunt patency and function rely on either repeated exposure to ionizing radiation¹⁻⁶ or invasive procedures such as shunt taps,

ABBREVIATIONS: **CI**, confidence interval; **CRO**, contract research organization; **CSF**, cerebrospinal fluid; **ED**, emergency department; **LR**, likelihood ratios; **MP**, micropumper; **NPV**, negative predictive values; **NS**, neurosurgery; **PPV**, positive predictive values; **TFE**, thermal flow evaluation

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radionuclide studies, and lumbar punctures. Unfortunately, these techniques have limited diagnostic accuracy in the emergency department (ED) setting and often lead to hospital admissions for observation.⁷⁻¹¹ It is well documented that true shunt failures often occur in the absence of ventriculomegaly¹²⁻¹⁴ and, conversely, that asymptomatic ventriculomegaly may require no intervention.^{15,16} Given that clinical manifestations of shunt obstruction are often non-specific, neurosurgeons sometimes disagree about the need for operative intervention. There is a need for accurate non-invasive methods for assessing shunt function to decrease unnecessary ED resource utilization, procedures,

and hospitalizations, as well as to augment clinical decision-making in the management of chronically shunted patients.

ShuntCheck III[®] (NeuroDx Development, Yardley, Pennsylvania) is an FDA-approved thermal flow evaluation (TFE) system used to detect and potentially quantify cerebrospinal fluid (CSF) flow in shunts. Open-label studies have reported that TFE accurately predicts CSF flow in shunts.¹⁷ A recent paper demonstrated that a modified TFE protocol with 2 ice-pack applications and a micropumper (MP) predicts non-progression to shunt revision surgery with a high percentage of patients in whom flow was detected not having shunt malfunction¹⁸ and may therefore hold significant clinical value as a rule-out test. However, it was unclear if diagnostic accuracy was improved by the micropumper or the second ice application, whether TFE could reliably be used in an emergent, high-pressure clinical setting, and whether clinical risk stratification of the study population prior to TFE could improve the diagnostic performance. Additionally, the study was unblinded and lacked an outcome measure that would not be influenced by TFE or other testing.¹⁸ To replicate prior findings in a larger population, we therefore performed a multicenter, blinded, prospective study in acutely symptomatic patients who received routine diagnostic evaluation for shunt malfunction. In this study, we compare the accuracy of 2 TFE protocols to that of neuro-imaging in identifying surgically confirmed obstruction within 7 d of presentation and hypothesize that both are non-inferior to neuro-imaging.

METHODS

Study Design and Patient Selection

Ten pediatric tertiary care centers participated in this prospective blinded study between April 2013 and March 2016. The research protocol was approved by the Institutional Review Board at each participating site. Informed consent was obtained prior to performing TFE, and patients were informed that test results would not be made available to the clinical team nor to the patient or family.

Target enrollment was calculated estimating a prevalence of 25% true obstruction in the study population² and a benchtop TFE sensitivity of 98%. A total of 85 true positives were needed to provide 80% power to reject that TFE sensitivity is <90% if the true sensitivity $\geq 97.5\%$, with an alpha level of 0.05 (nQuery Advisor 6.01, Statistical Solutions, Cork, Ireland). Assuming an attrition rate of 10%, total sample size was

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378 subjects, and the protocol rounded up to 400 consecutive series of patients between 3 and 29 yr of age presenting to the neurosurgery (NS) clinic or ED with symptoms sufficient to warrant routine diagnostic testing for potential shunt failure. Patients with multiple catheters, edema over the shunt, catheters not palpable over the clavicle, or where testing would interfere with clinical care, were excluded from the study.

Repeat patients were enrolled as incident cases of possible shunt malfunction if the interval separating presentations was greater than 1 mo, or if a surgical intervention happened in the interim. The 1-mo period had been identified as sufficient, on the basis of experience and prior investigations^{19,20} to demonstrate any true worsening of clinical status if there had been a slowly progressive case of true shunt obstruction in instances of suspected malfunction.

Thermal Flow Evaluation

Prior to the start of the study, operators received training to perform TFE from the device manufacturer. Testing was performed with the patient in either a sitting (preferred) or supine (where necessary) position, as previously described.^{17,18} Briefly, a segment of tubing passing over the clavicle was palpated and marked, facilitating placement of the adhesive thermosensors supplied in the kit to measure temperature over the tubing and immediately on either side. The sensors were then connected to a tablet computer running specially designed software to ensure operator blinding before the test was started.

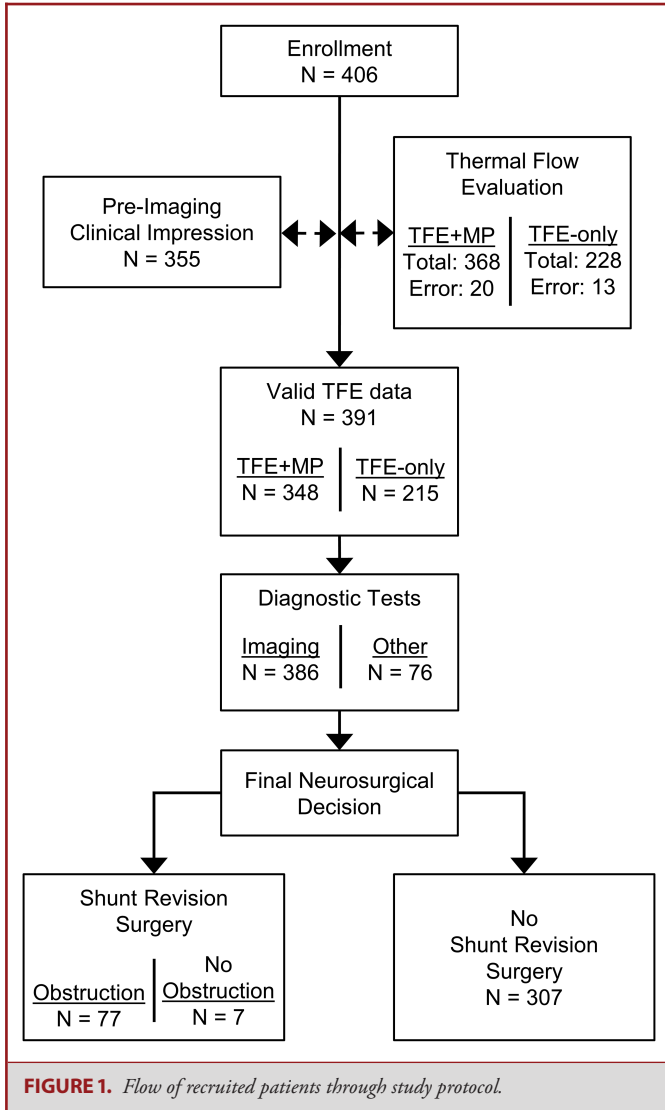
After 10 s of baseline temperature recording, an instant ice-pack was placed on the skin overlying the shunt immediately cephalad to the sensors for 60 s. One hundred and twenty seconds after removal of the ice-pack, the same ice-pack was reapplied for an additional 60 s. For TFE with micropumper (TFE+MP) tests, the activated micropumper was held in place over the shunt valve for 60 s following the end of the second ice-pack application, whereas patients in the TFE-only arm did not receive the micropumper application, and the second ice-pack application lasted for 120 s instead. Temperature data collection continued for an additional 240 s, and total test duration was 550 s. For patients who underwent both the TFE+MP and TFE-only procedures in the same visit, a heating pad was applied to the skin for 60 s, followed by a 5-min wait to establish re-equilibration between tests. The manufacturer-specified threshold of a temperature drop $\geq 0.2^{\circ}\text{C}$ was used to classify flow-detected vs flow-not-detected results.^{17,18,21}

Clinical Data Collection

All clinical and research team members at each site were blinded to TFE results until study completion. Blinding was ensured by modifying the tablet computers so that they did not allow access to raw data or test results.

A preimaging determination of the likelihood of progression to shunt revision surgery (unlikely/not unlikely) for each subject was made by the first attending physician to examine the patient, in most cases an ED physician (79% ED; 21% NS). This assessment was based on the physician's unstructured clinical judgment, considering clinical history and physical examination alone and codified as a categorical response.

The reference standard for shunt failure was shunt revision surgery with visually confirmed shunt obstruction within 7 d of TFE. All decisions to progress to surgery were based on clinical decision-making protocols currently in place at each center. Determination of shunt obstruction at surgery was made by the attending neurosurgeon when any of 4 observations occurred: a disconnected shunt, a complete lack



of observable flow, proximal catheter flow less than 2 drops in 20 s, or complete distal obstruction when checked with a manometer.

Final radiologist interpretations were used to classify neuro-imaging results as “not enlarged” if the ventricular size was unchanged or decreased, or “enlarged” if the size was greater than in the most recent baseline study.

Patients’ charts were reviewed 7 d after presentation to confirm clinical progression, and all clinical information was recorded on a case report form for each patient. A total 7-d follow-up was chosen to avoid missing patients presenting initially with sub-acute obstruction, but whose signs and symptoms progressed within a time-frame that is clinically sensible to attribute the original presentation to the shunt obstruction.

Data Handling

TFE results were uploaded to the device manufacturer blind to any clinical information, who then forwarded them to a contract research

TABLE 1. Demographic and Clinical Information for Study Population

	TFE+MP group N = 348	TFE-only group N = 215
Sex		
Female	156 (45%)	100 (47%)
Male	192 (55%)	115 (53%)
Age		
Median (years)	12	11
Distribution:		
2-6 years	74 (21%)	50 (23%)
7-11 years	96 (28%)	58 (27%)
12-16 years	102 (29%)	65 (30%)
17-21 years	44 (13%)	24 (11%)
22-26 years	24 (7%)	13 (6%)
>26 years	8 (2%)	5 (2%)
Cause of hydrocephalus		
Spina bifida	52 (15%)	37 (17%)
Neonatal IVH	70 (20%)	40 (19%)
Brain tumor	37 (11%)	26 (12%)
Post-meningitis	12 (4%)	8 (4%)
Post-TBI	3 (1%)	3 (1%)
Aqueductal stenosis	11 (3%)	6 (3%)
Dandy-Walker	17 (5%)	11 (5%)
Other (congenital)	101 (29%)	54 (25%)
Other (non-congenital)	21 (6%)	10 (5%)
Unknown	24 (7%)	20 (9%)

As noted in the text, the TFE+MP and TFE-only groups overlap, for a total of 391 valid tests in 406 enrolled patients.

organization (CRO; ACI Clinical, Bala Cynwyd, Pennsylvania). Case report forms with clinical information for each subject were uploaded independently by the sites to the CRO.

Statistical Analysis

All statistical analysis was conducted based on the blind interpretation of test results. We calculated the sensitivity, specificity, positive and negative predictive values (PPV and NPV), and positive and negative likelihood ratios (LR+ and LR-) of TFE only, TFE+MP, and neuro-imaging alone in all patients as well as those categorized as “unlikely” to progress to revision surgery by clinical gestalt. Differences in sensitivity between TFE and neuro-imaging were calculated using McNemar’s test and compared to a prospectively determined a priori non-inferiority margin of –2.5%. All analyses were performed using IBM SPSS Statistics v24.0 software (IBM Corporation, Armonk, New York) and MedCalc v19.1 (MedCalc Software, Ostend, Belgium).

RESULTS

Study Participants

A total of 406 patients were enrolled, and TFE was successfully completed in 391. A total of 77 patients progressed to surgery for visually confirmed shunt obstruction, and 91% of these were operated upon within 48 h of presentation.

TABLE 2. Diagnostic Accuracy of Thermal Flow Evaluation and Neuro-Imaging in Predicting Surgically Verified Shunt Obstruction: Summary Statistics

	All Patients				Pre-Imaging Clinical Impression: Unlikely			
	TFE+MP group		TFE-only group		TFE+MP group		TFE-only group	
	TFE+MP result	Imaging result	TFE-only result	Imaging result	TFE+MP result	Imaging result	TFE-only result	Imaging result
Prevalence (%)	20	20	14	14	8	8	7	7
Sensitivity (%)	90	76	100	77	100	73	100	67
(95% CI)	(80-96)	(65-86)	(88-100)	(58-90)	(78-100)	(45-92)	(66-100)	(30-93)
Specificity (%)	50	90	60	92	49	93	59	94
(95% CI)	(44-56)	(86-93)	(53-67)	(87-95)	(42-57)	(87-97)	(50-68)	(88-98)
Negative PV (%)	95	94	100*	96	100*	98	100*	97
(95% CI)	(91-98)	(91-96)		(93-98)		(95-99)		(94-99)
Positive PV (%)	30	66	29	61	14	48	16	46
(95% CI)	(27-33)	(57-74)	(25-33)	(48-72)	(12-16)	(33-63)	(13-19)	(27-67)
LR +	1.8	7.8	2.5	9.5	2.0	10.9	2.5	11.3
(95% CI)	(1.6-2.1)	(5.3-11.4)	(2.1-3.0)	(5.6-16.0)	(1.7-2.3)	(5.8-20.3)	(2.0-3.0)	(4.8-26.6)
LR -	0.2	0.3	0*	0.3	0*	0.3	0*	0.4
(95% CI)	(0.1-0.4)	(0.2-0.4)		(0.1-0.5)		(0.1-0.7)		(0.1-0.9)

This table summarizes the analysis of the data shown in Figures 2 and 4.

*95% CIs could not be calculated for NPV of 100% or LR- of 0. (TFE+MP, thermal flow evaluation with micropumper; TFE-only, thermal flow evaluation without micropumper; 95% CI, 95% confidence interval; PV, predictive value; LR, likelihood ratio).

Note: Negative and positive predictive values are affected by changes in prevalence and may differ between practices. However, sensitivity and specificity are intrinsic qualities of the test and remain constant.

The first 176 were tested with TFE+MP (Figure 1 and Table 1). An interim review at 12 mo and the completion of a concurrent single-site study¹⁸ led to the expansion of the testing protocol to include repeat tests, first without (TFE-only), then with the micropumper (TFE+MP). The goal of this modification was to isolate the value of the micropumper vs the additional application of the cold stimulus alone. A total of 172 patients had both versions of the test, and 43 received exclusively TFE only due either to time constraints or patient preference to perform only one test. The double-tested patients allow a comparison of the 2 techniques.

Concordance of flow detection among those receiving both versions of the test was found in 94 cases (66%). However, in patients with visually confirmed occlusions, concordance occurred in 24 of 25 (96%). We therefore show results for the two tests separately and will compare the techniques later.

Thermally Detectable Flow Predicts Non-Progression to Surgery for Obstruction and is Non-Inferior to Neuro-Imaging

The observed prevalence of visually confirmed shunt obstruction in all patients was 20% for TFE+MP (n = 348) and 14% for TFE only (n = 215). Measures of diagnostic accuracy are detailed in Table 2, and contingency tables are shown in Figure 2A (TFE+MP) and Figure 2B (TFE only).

Ninety-nine percent of patients within the TFE+MP arm, and all TFE-only patients, had neuro-imaging performed as part of their clinical evaluation (Figure 2C and 2D). In both groups, neuro-imaging demonstrated lower sensitivity, NPV, and LR-compared to TFE (Table 2).

The lower bound of the 95% CI around the difference in sensitivity between TFE and neuro-imaging did not cross the prospectively determined a priori non-inferiority margin of -2.5% for either protocol. Therefore, the sensitivity of TFE was non-inferior to neuro-imaging for diagnosing shunt malfunction (Figure 3).

Neuro-Imaging Has Higher Specificity Compared to TFE in Identifying Patients With Shunt Obstruction Requiring Surgical Intervention

Neuro-imaging, on the other hand, exhibited higher specificity, PPV, and LR+ compared to TFE across all groups. The probability of visually confirmed obstruction is about twice as high after imaging showing ventricular enlargement vs TFE showing flow not detected (Table 2).

Diagnostic Accuracy of TFE is Higher Among Those With a Preimaging Clinical Impression of “Unlikely to Require Shunt Revision”

The prevalence of visually confirmed obstruction in patients determined on initial preimaging evaluation to be unlikely to

		All Patients									
		TFE+MP group			TFE-only group						
Thermal Flow Evaluation	A	Surgery + Obstruction			Total	Surgery + Obstruction			Total		
		+	-			+	-				
		+ (FND)	61	141		202	+ (FND)	30		74	104
		- (FD)	7	139		146	- (FD)	0		111	111
		68	280	348		30	185	215			
Ventricular Imaging	C	Surgery + Obstruction			Total	Surgery + Obstruction			Total		
		+	-			+	-				
		+ (Enlarged)	52	27		79	+ (Enlarged)	23		15	38
		- (Not Enlarged)	16	248		264	- (Not Enlarged)	7		170	177
		68	275	343		30	185	215			

FIGURE 2. Thermal Flow Evaluation: Prediction of Progression to Surgery for Shunt Obstruction in All Patients. **A**, TFE+MP predicted obstruction at surgery with a sensitivity and specificity of 90% and 50% respectively. **B**, TFE-only demonstrated a sensitivity and specificity of 100% and 60% respectively, approximately 10% higher than TFE+MP. **C**, Imaging in the TFE+MP cohort exhibited a sensitivity of 76% and a specificity of 90%. **D**, Imaging in patients who received TFE-only tests showed a similar accuracy as in patients who received TFE+MP tests, with a sensitivity of 77% and specificity of 92%. (TFE+MP, thermal flow evaluation with micropumper; TFE-only, thermal flow evaluation without micropumper; FND, flow not detected; FD, flow detected).

progress to shunt revision surgery was about 7% to 8%, down from 14% to 20% in all patients (Table 2 and Figure 4).

Of note, sensitivity of the TFE+MP testing protocol increased from 90% in all patients to 100% in “unlikely” patients, whereas LR- decreased from 0.2 to 0.0. This indicates a substantial further decrease in the post-test probability of progression to surgery following a flow-detected result. Neither sensitivity nor LR- changed for neuro-imaging in the same patients (Table 2).

DISCUSSION

Our earlier report, which did not involve operator blinding, pointed to the utility of thermal detection as a “rule-out” test for obstructive shunt malfunction. It also raised several questions, including replicability and generalizability of the findings in a blinded, emergent setting.¹⁸ Using a large, multi-site, prospective, operator-blinded clinical study design, we tested acutely symptomatic pediatric and adolescent patients who presented to the ED and neurosurgical clinic, and who concurrently received routine diagnostic evaluation. The present study confirms and extends the results of the single center study: thermal detection of shunt flow may be an effective confirmatory test to support an initial clinical impression of a functioning shunt in the management of chronically shunted patients, and

the results are generalizable to a broader population of patients being evaluated at pediatric EDs.

The prediction of non-progression to surgery when TFE confirms flow, either with or without the micropumper, was the most robust and compelling finding in this study. These results compare favorably to those for neuro-imaging, both in the same patients and in other studies,²⁰ and support our earlier findings that the true utility of TFE may lie in correctly identifying patients presenting with suspected shunt malfunction symptoms who do not require immediate surgical intervention.¹⁸

The results from TFE+MP and TFE-only (Figure 2A and 2B) indicate that there is no advantage to using the micropumper in an emergent clinical setting. In fact, TFE+MP showed flow in seven cases in which the shunts were significantly occluded at the time of surgery. Perhaps micropumper action forces flow across an obstruction that would otherwise prevent passage of sufficient CSF under physiological conditions. For purposes of screening patients for shunt obstruction in emergent settings, it is therefore reasonable to recommend performing TFE with the double ice application (TFE only) and without the micropumper.

New to this study is a specific preimaging question about the likelihood, in the opinion of the first evaluating attending physician, of the patient progressing to surgery based on clinical

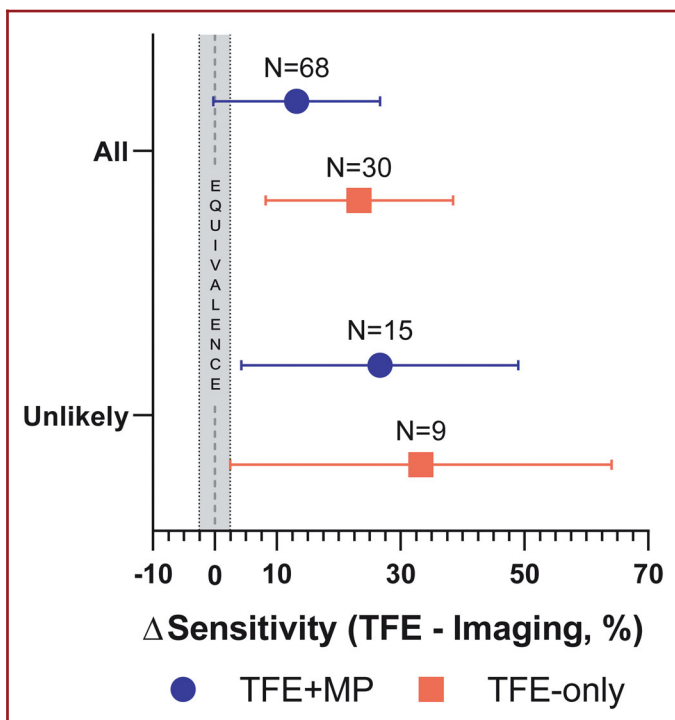


FIGURE 3. Non-inferiority of TFE to imaging. The difference in sensitivities between TFE (either with or without micropumper), and neuro-imaging did not exceed the prospectively determined a priori non-inferiority margin of -2.5% in all patients (TFE+MP: 13.24%, 95%CI: -0.23 -26.70%; TFE: 23.33%, 95% CI: 8.20-38.47%), as well as among clinically “unlikely” patients (TFE+MP: 26.67%, 95% CI: 4.29-49.05%; TFE: 33.33%, 95% CI: 2.53-64.13%). (TFE+MP, TFE with micropumper; TFE-only, TFE without micropumper).

gestalt. Attending physicians evaluated patients on presentation in advance of any diagnostic testing. Thermal testing showed a high sensitivity in patients deemed “unlikely” to require shunt revision surgery for their symptoms. In this cohort, TFE+MP correctly identified all 15 patients with obstruction seen at surgery. TFE+MP compared favorably as a rule-out test to imaging; however, risk stratification did not affect sensitivity and NPV for TFE only, which were already 100%.

There are significant gaps in the literature, and little to no evidence-based guidelines on the appropriate management of suspected shunt malfunction.²² In this setting, it is common to evaluate patients with suspected shunt malfunction with imaging and other more invasive testing.^{1-6,20} Entry into this study, too, required sufficient clinical suspicion that additional diagnostic evaluation, almost always radiographic testing, would be pursued. However, patients in the “unlikely” group who also had a flow-detected result on TFE had a very low probability of needing shunt revision surgery. This finding suggests that clinicians may consider the use of TFE to confirm their clinical impression and, therefore, spare patients imaging and other invasive testing. This

would not only help reduce costs, but more importantly, in the case of computed tomography, reduce repeated exposure ionizing radiation.^{1,23-25}

The sensitivity of thermal flow testing both with and without micropumper was non-inferior to neuro-imaging in ruling out shunt obstruction in all patients, as well as those assessed by first-contact clinicians as being “unlikely” to require surgery in advance of neuro-imaging (Figure 3). However, neuro-imaging had higher specificity, positive predictive values, positive LR, and post-test probabilities of visually confirmed obstruction (Table 2 and Table, Supplemental Digital Content), indicating that a scan showing enlarged ventricles may be better than TFE at ruling in shunt malfunction.

There may be several plausible explanations for the seemingly high incidence of the finding of flow not detected in patients without shunt obstruction. First, we and others have previously demonstrated that CSF flow within shunts in Vivo is intermittent.^{17,26-29} In addition, the testing algorithm is programmed conservatively to report flow not detected when activity of the test subject could introduce noise into the thermal signal. This could be an important consideration when attempting to test actively moving children. Actual flow may fall below the threshold for automated detection, which is an inherent limitation of all automated determinations. To enable binary outcome event comparison, we adopted the default temperature cut-off recommended by the manufacturer in classifying flow-not-detected vs flow-detected results. This cutoff, as reported previously,^{17,21} is conservatively chosen to minimize the probability of false negatives, thus limiting the risk of missing patients with shunt obstructions. Previously, we reported that ROC curve analysis indicates that a lower threshold would potentially improve specificity without significantly lowering sensitivity.¹⁸ Further data collection and improvements in the algorithms, including serial retesting of chronically shunted patients, will allow the manufacturer to build better precision into the device’s algorithms.

Clinical Utility of TFE: Moving Toward Integration Into Standard of Care

Given these results and the better performance of neuro-imaging as a rule-in test for shunt obstruction, we believe that TFE, as with many diagnostic tests, is best used in conjunction with clinical judgment and other diagnostic data and not considered a standalone test for shunt malfunction. We can envision the integration of TFE into routine clinical evaluation of suspected shunt malfunction, as depicted in one possible decision tree shown in Figure 5. The results shown apply only to this retrospective dataset, but the outline of the decision tree suggests means by which TFE can enhance current clinical options.

Given the demonstrated utility of TFE as a rule-out test, patients who are clinically classified as low risk for shunt malfunction and have flow detected by TFE may be strongly considered for discharge without neuro-imaging (Figure 5,

Pre-Imaging clinical impression - Unlikely										
		TFE+MP group			TFE-only group					
Thermal Flow Evaluation	A	Surgery + Obstruction			Total	Surgery + Obstruction				
			+	-			+	-	Total	
		+ (FND)	15	93		108	+ (FND)	9	49	58
		- (FD)	0	90		90	- (FD)	0	71	71
		15	183	198		9	120	129		
Ventricular Imaging	C	Surgery + Obstruction			Total	Surgery + Obstruction				
			+	-			+	-	Total	
		+ (Enlarged)	11	12		23	+ (Enlarged)	6	7	13
		- (Not Enlarged)	4	166		170	- (Not Enlarged)	3	112	115
		15	178	193		9	119	128		

FIGURE 4. Thermal Flow Evaluation: Prediction of Progression to Surgery for Shunt Obstruction in Patients Unlikely to Require Shunt Revision on Pre-Imaging Clinical Evaluation. **A**, In patients deemed “unlikely” to progress to shunt revision surgery on initial pre-imaging clinical evaluation, TFE+MP predicted surgically verified shunt obstruction with 100% sensitivity and 49% specificity. **B**, TFE-only again demonstrated a high sensitivity of 100% and specificity of 59%. **C**, Imaging in the TFE+MP group showed a sensitivity of 73% and a specificity of 93%. **D**, Imaging in patients who received TFE-only tests showed a sensitivity of 67% and specificity of 94%. (TFE+MP, thermal flow evaluation with micropumper; TFE-only, thermal flow evaluation without micropumper; FND, flow not detected; FD, flow detected).

terminus I). With greater caution, patients categorized by clinicians as high-risk but with a negative imaging result (ventricles not enlarged) may potentially be discharged without further invasive testing or inpatient observation following detection of flow on TFE, and advised to follow-up in clinic (Figure 5, terminus IV). However, this determination would require further study to account for prior patterns of malfunction in such patients. Conversely, patients who have enlarged ventricles on neuroimaging have a high likelihood of requiring surgical shunt revision (Figure 5, termini III and VI). Retrospective application of this decision tree to our sample demonstrated a substantial reduction in number of imaging scans and exposure to ionizing radiation, uncomfortable invasive tests, and admissions for observation (Figure 5, inset). Less clear are the decision paths where flow is not detected by TFE in the absence of ventriculomegaly (Figure 5, termini II and V).

These approaches to integrating TFE may be considered as possible improvements in care; however, any guidelines on the use of TFE in the clinical management of acute shunt malfunction would require further studies to stratify these groups. As always, providers should employ any and all measures to make the best judgment about the functionality of a shunt.

Limitations

All subject recruitment was performed at pediatric tertiary care centers with subspecialty trained faculty, in which suspected shunt malfunction is a common presentation. As such, generalizability of the study's findings to community clinical settings may be limited, in which physicians either lack subspecialty training or encounter such patients infrequently.

A total 7 d of follow-up was selected in the study design to capture slowly evolving episodes of obstruction, and almost all patients who had surgery were in fact operated on within 48 h of presentation. The study is not designed to predict the impact of flow determinations on longer term function of the shunt.

Multiple patients received both versions of the test on the same day. In these, a chemical heating pad was applied to the skin followed by a 5-min wait to re-establish baseline skin temperature between test. It is possible optimal re-equilibration did not occur, however, as noted previously; there was a high degree of concordance in test results.

Lastly, the sample size of the current study is not large enough to evaluate the performance of TFE in relevant subpopulations. Analyses of subgroups based on age, etiology of hydrocephalus, type of hardware, or prior patterns of malfunction (such as history

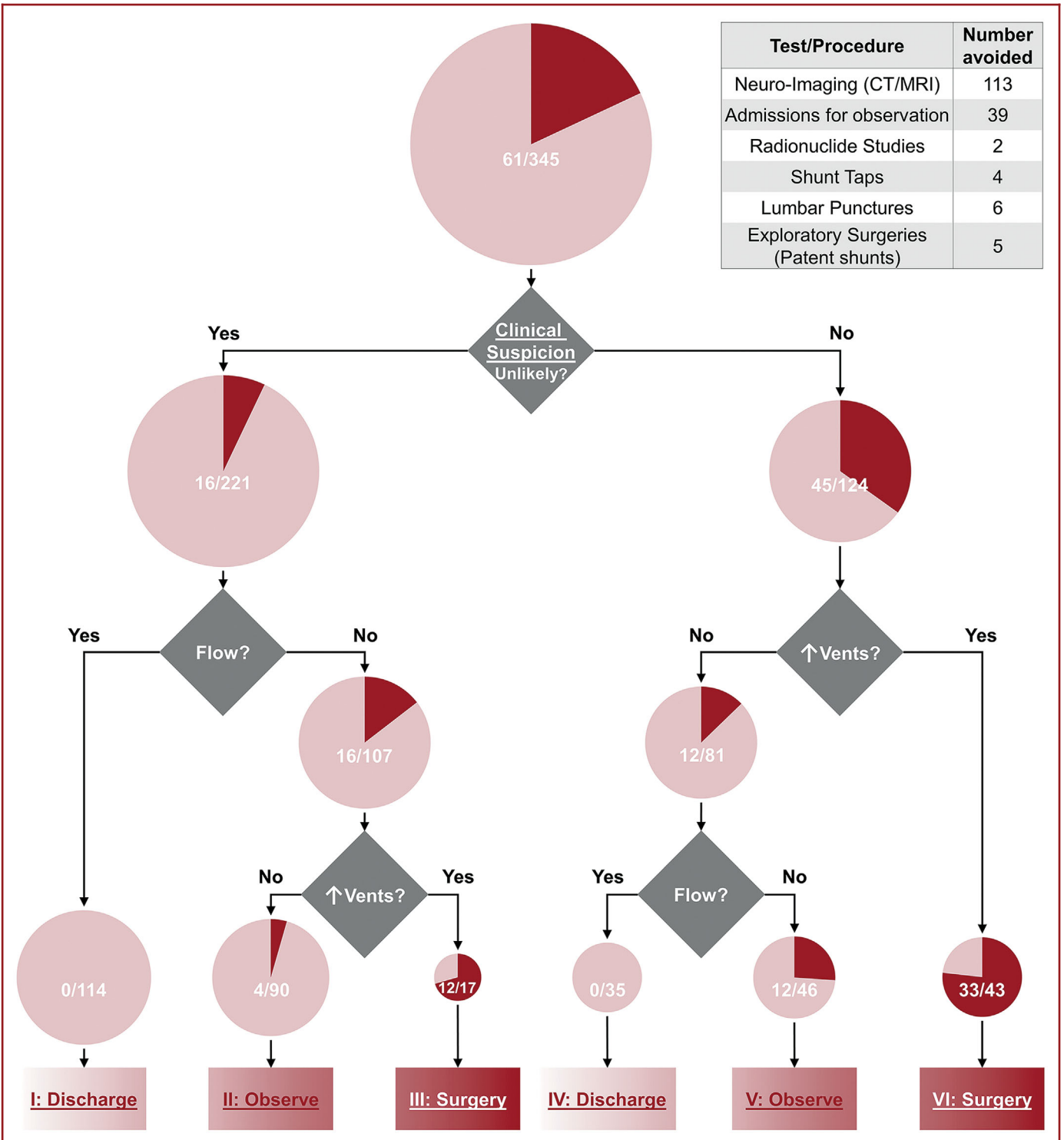


FIGURE 5. Clinical utility of TFE as a rule-out test. Given the demonstrated utility of TFE as a rule-out test, we can envision the integration of TFE into routine clinical evaluation of suspected shunt malfunction in conjunction with clinical judgment and other diagnostic data, as depicted in one possible decision tree shown here. The proposed algorithm was then applied post hoc to the pooled study sample. A complete dataset (TFE result, neuro-imaging result, and preimaging clinical impression) was available for 345 patients. The dark wedges represent the proportion of patients with confirmed obstruction at surgery, and the area of the circle represents the total number of patients at each respective node. Absolute numbers are given at the bottom of each circle. The numerical data shown in the figure apply only to this study population, but the outline

FIGURE 5. (Continued.) of the decision tree suggests means by which TFE can enhance current clinical options. Terminus I: patients who are clinically classified as low risk for shunt malfunction and have flow detected by TFE may be strongly considered for discharge without imaging. Terminus IV: with greater caution, patients categorized by clinicians as high-risk preimaging but without enlarged ventricles may potentially be discharged without further invasive testing or inpatient observation following detection of flow on TFE and advised to follow-up in clinic. However, this determination would require further study to account for prior patterns of malfunction in such patients. Termini III and VI: conversely, patients who have enlarged ventricles on imaging have a high likelihood of requiring surgical shunt revision. Termini II and V: these decision paths, in which flow is not detected by TFE in the absence of ventriculomegaly, are less clear, and additional large sampled studies will be required to further resolve these groups. INSET: if the decision pathway shown had been prospectively applied to the study group, imaging might have been avoided in “unlikely” patients with flow confirmed, and invasive testing and admissions for observation might have been avoided in a number of other patients with confirmed shunt flow. Validation with a prospective dataset will be needed to precisely determine the actual savings. These approaches to integrating TFE may be considered as possible improvements in care; however, any guidelines on the use of TFE in the clinical management of acute shunt malfunction would require further studies. As always, providers should employ any and all measures to make the best judgment about the functionality of a shunt.

of ventricular volume change or lack of change in prior malfunctions), might yield somewhat different results, but the intent for this study was to average over many patients and centers. Age and developmental delay may also be factors in the likelihood of cooperation with TFE (as for any prolonged medical test such as imaging). Studies to examine these subgroups would need a different design to power for such determination.

CONCLUSION

Use of a thermal flow detection device may help rule out a shunt malfunction and may be particularly useful in patients where the clinical impression is that shunt malfunction is unlikely. In such patients with thermally detected shunt flow, ventricular imaging may be unnecessary, and a decision to avoid invasive tests or admission for observation may be obviated. The use of a micropumper device to enhance flow did not improve the diagnostic accuracy in this situation.

Disclosures

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Supplemental Digital Content. Table. Definitions of terms relating to diagnostic accuracy of medical tests.
