Practice on an Augmented Reality/Haptic Simulator and Library of Virtual Brains Improves Residents' Ability to Perform a Ventriculostomy

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Introduction: Ventriculostomy is a neurosurgical procedure for providing therapeutic cerebrospinal fluid drainage. Complications may arise during repeated attempts at placing the catheter in the ventricle. We studied the impact of simulation-based practice with a library of virtual brains on neurosurgery residents' performance in simulated and live surgical ventriculostomies.

Methods: Using computed tomographic scans of actual patients, we developed a library of 15 virtual brains for the ImmersiveTouch system, a head- and hand-tracked augmented reality and haptic simulator. The virtual brains represent a range of anatomies including normal, shifted, and compressed ventricles. Neurosurgery residents participated in individual simulator practice on the library of brains including visualizing the 3-dimensional location of the catheter within the brain immediately after each insertion. Performance of participants on novel brains in the simulator and during actual surgery before and after intervention was analyzed using generalized linear mixed models.

Results: Simulator cannulation success rates increased after intervention, and live procedure outcomes showed improvement in the rate of successful cannulation on the first pass. However, the incidence of deeper, contralateral (simulator) and third-ventricle (live) placements increased after intervention. Residents reported that simulations were realistic and helpful in improving procedural skills such as aiming the probe, sensing the pressure change when entering the ventricle, and estimating how far the catheter should be advanced within the ventricle.

Conclusions: Simulator practice with a library of virtual brains representing a range of anatomies and difficulty levels may improve performance, potentially decreasing complications due to inexpert technique.

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Ventricles are fluid-filled spaces deep within the brain. Ventriculostomy, the insertion of a catheter into the ventricle, is a neurosurgical procedure for measuring the intracranial pressure and providing therapeutic cerebrospinal fluid drainage in situations of increased intracranial pressure such as brain injury, hydrocephalus, and intracranial tumors.[1] If the surgeon misses the ventricle, the catheter is removed and reinserted at a different angle. Complications such as infection and intracranial hemorrhage increase with the number of placement attempts.[2]

Ventriculostomy is frequently performed by neurosurgery residents in their second or third year of training. Resident physicians may not have an opportunity to perform ventriculostomies on patients with less common compressed or shifted ventricles until asked to intervene on an emergent basis; in these situations, catheters are more difficult to place, frequently requiring more attempts before successful placement. Simulation has the potential to provide residents with practice on both common and uncommon anatomic or clinical presentations.[3] Deliberate practice[4] in the simulated environment may lead to improved skills and translate into improved surgical performance and patient outcomes.[5]

In this study, we developed an extended library of 15 virtual brains for a ventriculostomy simulator, used the library to permit repeated deliberate practice on cases that exhibit a range of normal and abnormal anatomies, and studied the impact of simulator practice on both simulated and live surgical performance. We expected that practice on the library of brains would improve residents' ability to use the computed tomographic (CT) scan of the brain to

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visualize the location of the ventricle and the desired location of the catheter tip, correctly aim the catheter toward the ventricle, sense the pressure change when entering the ventricle, and estimate how far the catheter should be advanced within the ventricle. We hypothesized that these improved skills would result in more successful performance in both simulated and live surgeries, as indicated by the probability of successful cannulation and optimal placement of the catheter tip in the ipsilateral lateral ventricle.

METHODS

The institutional review board of the University of Illinois at Chicago approved the study protocol.

Phase 1: Simulated Brain Library Development and Pilot Testing

ImmersiveTouch is a simulation system that integrates a haptic device with a head-and-hand tracking system and a high-resolution high–pixel density stereoscopic display.[6–8] The ImmersiveTouch virtual head (skin, skull, brain, and ventricles) is constructed based on high-resolution CT data. The user views a stereoscopic image of the virtual head reflected on a half-silvered mirror while grasping a haptic stylus under the mirror (Fig. 1). The perfect overlap of the virtual catheter 3-dimensional (3D) image with the haptic stylus leads the user to feel as though he/she is holding the catheter; force feedback allows the user to feel when the "catheter" touches the surface of the head or brain. The part-task simulation provides users with several "predrilled" burr holes in standard positions for catheter insertion. The use of CT scans from actual patients ensures that the 3D virtual models are realistic and that anatomic challenges correspond to the challenges actually encountered by neurosurgeons.

Visual and haptic feedback duplicates the visual and tactile feedback obtained during the actual procedure: visual feedback about how far the probe has been inserted into the brain and at what angle and tactile feedback about the resistance of the brain matter and the subtle "pop" felt when entering the ventricle. Uniquely, the simulator allows the surgeon to "open" the virtual head to see the location of the probe within the brain.

Three main types of ventricles, normal, shifted, or compressed, are encountered in ventriculostomy procedures. Different challenges are associated with each of the ventricle types; accordingly, we developed 5 cases of each of the 3 types of ventricles. Computed tomographic scan images associated with each virtual brain were archived for viewing before the simulated surgery. This corresponds to actual practice during surgery and helps residents learn to use the CT scan to aid in estimating the location of the ventricle and of the desired location of the catheter tip.

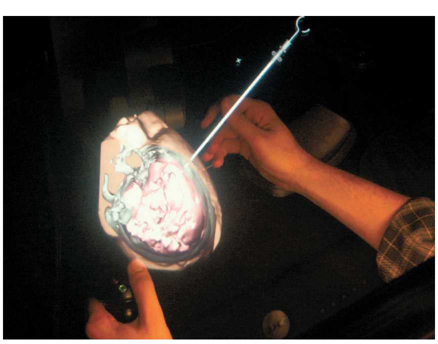

FIGURE 1. Inserting the catheter in the ImmersiveTouch virtual projection of a brain (skin and skull made transparent to show the underlying brain).

Two senior neurosurgeons piloted the library by performing ventriculostomy procedures on each of the virtual brains and providing feedback regarding the fidelity and difficulty of each virtual brain.

Phase 2: Research Study

Study Design

A before-after approach was used to evaluate the effectiveness of practice on simulated brains to improve performance of ventriculostomy: (1) on novel brains presented in the simulator and (2) during live surgery. Our intervention focused exclusively on the critical skill of inserting the catheter into the ventricle.

Data Sources/Collection

Neurosurgery residents were recruited from 4 Chicago neurosurgery training programs. Each resident participated in a single 2- to 3-hour practice session with the simulator. To facilitate transfer to live surgical procedures, residents practiced on 4 different cases of each type of ventricle, with open visualization feedback after each attempt.

Practice Session Protocol

Practice began with the least difficult brain of each type (as determined by pilot testing of the library), followed by random presentation of the remaining virtual brains. Similar to the process in actual surgery, the CT scan image associated with each case was provided before each simulated procedure.

Residents were allowed up to 10 minutes of practice per case before switching to the next case. Each resident encountered 12 cases, for a maximum of 2 hours of practice. Rest breaks were imposed every 30 minutes.

Measures

Competency indicators (listed in the next section) were collected immediately before and after practice, using a subset of virtual brains designated for assessment use. Pretests and posttests included 1 case of each ventricle type; different cases were used for the pretest and posttest to avoid a practice effect. Pretest cases were included in the subsequent practice set. Residents were reassessed on the posttest cases approximately 1 month after the initial practice session to evaluate the decay of effect over time.

Assessment Protocol

To orient residents to the simulator, before the pretest, each resident was presented with a hydrocephalic ventricle practice brain and allowed several attempts to cannulate the ventricle.

Pretest and posttest procedure is as follows:

Step 1: The resident was shown the CT scan of one of the virtual brains.

Step 2: The resident was presented with the virtual representation of that brain in the simulator.

Step 3: The resident made 3 ventriculostomy attempts using the simulator.

After each attempt, the resident was told whether they were successful—that is, whether the tip of the catheter was located within the ventricle. This emulates the actual surgery, in which there is immediate feedback about the success of the procedure (if the procedure is successful, fluid emerges from the catheter). The resident made 3 separate attempts to cannulate the ventricle of each brain, whether or not initial attempts were successful, to increase the number of available data points for each resident. Competency indicators (dependent variables) were recorded after each attempt.

In both the pretest and the posttest, the 3-step procedure mentioned previously was repeated 3 times, once with a normal-ventricle brain, once with a shifted ventricle, and once with a compressed ventricle, in that order. The pretest and posttest sets were chosen to be of equivalent difficulty based on pilot testing. Half of the residents used set A as a pretest and set B as a posttest, and half of the residents used set B as the pretest and set A as the posttest.

Live Surgery Assessment Procedure

To assess the impact of practice on actual surgical procedures, competency indicators were collected from live ventriculostomies performed by participating residents in the 6 months immediately before and 1 month immediately after their practice sessions. Residents completed a data collection form immediately after each live procedure; a research collaborator reviewed patient records and postprocedure CT scans to obtain information about catheter location and immediate complications.

Statistical Analysis

Simulator Data

A series of generalized linear mixed models were fitted to the data using SAS 9.2 PROC GLIMMIX, with full maximum likelihood estimation (METHOD = QUAD) and either logistic or normal distributions, depending on the nature of the outcome. In each model, random intercepts were fitted for residents using an unstructured covariance matrix, to account for clustering of responses within resident. Predictors in each model were assessment time (before intervention, after intervention, or follow-up), type of brain (normal, shifted, or compressed), individual brain nested within type, attempt number (1, 2, or 3), year of resident in program (1–7), and number of live ventriculostomies performed by the resident in the last 12 months. The total number of ventriculostomies performed by the resident was found to be highly correlated with the resident's year in program and was excluded from the model to avoid multicollinearity.

Models were fitted to the following outcomes: successful catheter placement in the ventricle, ipsilateral (vs. contralateral) placement, catheter depth (in centimeters), and distance (in millimeters) of catheter tip from the foramen of Monro (FOM) for those attempts where placement was successful. When overall effects of time were significant, planned contrasts were conducted between before intervention and after intervention and between before intervention and follow-up.

Field (Live Surgery) Data

A series of generalized linear mixed models were fitted to the data using SAS 9.2 PROC GLIMMIX, with full maximum likelihood estimation (METHOD = QUAD) and either logistic or normal distributions, depending on the nature of the outcome. In each model, random intercepts were fitted for residents using an unstructured covariance matrix, to account for clustering of responses within resident. Predictors in each model were assessment time (before or after intervention) and year of resident in program.

Models were fitted to the following outcomes: whether cannulation was successful, whether cannulation succeeded on the first attempt, ipsilateral (vs. contralateral) placement, entry into the lateral (vs. third or other) ventricle space, hemorrhage, and catheter depth (in centimeters).

Program Evaluation

Residents evaluated the practice sessions using a written questionnaire that elicited feedback regarding: clinical fidelity of the simulations, difficulty of the task, perceived impact of the practice session, participant satisfaction, and suggestions for improvement. The questionnaire included both Likert-type category rating items and free response items. Feedback was solicited at the conclusion of the practice session (after the posttest) and at the conclusion of the follow-up session.

RESULTS

A library of 15 virtual brains with their surrounding heads was developed and piloted, including 5 brains for each category of normal, compressed, and shifted ventricles (Fig. 2).

Evaluation of Simulator Practice Sessions

From 4 Chicago neurologic surgery programs, 16 trainees participated in the simulation practice sessions: 7 postgraduate year 1 (PGY1) (first year) residents, 4 PGY2 residents, 1 PGY3 resident, 4 PGY4 and up residents. Residents reported performing a median range of 16 to 20 live ventriculostomy procedures in the past 12 months and 41 to 50 procedures since beginning residency. Twelve subjects (75%) returned for the follow-up posttest and completed a follow-up questionnaire from 19 to 64 days after practice [mean (SD), 47 (11.7) days]. Subjects had performed a mean of 5 live ventriculostomy procedures in the interval between the practice session and the follow-up session (range, 0–20; SD, 6.0).

Residents were allowed to structure their own practice approach. Most residents attempted to enter the ventricle, opened the virtual head to see where they ended up, rotated the 3D model to get views from different angles, tried again until successful, and then moved onto the next virtual brain. Some residents took a systematic exploratory approach. For example, 1 resident systematically explored the boundaries of the ventricle, testing to see what angles of insertion obtained the best results and how far he could insert the probe before exiting the other side of the ventricle. Another resident focused on perceiving the tactile change on entry into the ventricle by inserting the probe to just before the ventricle boundary and then advancing in very small increments, opening the brain each time to see if he had reached or passed the boundary.

FIGURE 2. The library of virtual brains. Ventricles appear in blue.

Several residents expressed a desire to be able to choose their burr hole location rather than being limited to a preexisting location. (The situation of a previously drilled burr hole does occur clinically, for example, when a catheter needs to be reinserted.) Similarly, some residents expressed frustration with the inability to place their nondominant hand on the virtual patient's head, which would typically aid them in landmark location.

Simulation Pretest and Posttest Assessment Data

Sixteen residents generated a total of 397 simulated ventriculostomy attempts, with 3 attempts per resident per brain type per time.

There were significant effects of time, brain type, and individual brain within type on *successful placement* (see Table 1 for unadjusted success rates). The overall adjusted probability of successful cannulation was 12% before intervention, 32% after intervention, and 26% at follow-up. Relative to preintervention performance, individual residents were more successful immediately after intervention [odds ratio (OR), 3.43; 95% confidence interval (CI), 1.74–6.77; $P < 0.001$] and at follow-up (OR, 2.59; 95% CI,

TABLE 1. Resident Performance on the Simulator

	Proportion of Successful Attempts (Unadjusted) (16 Residents, 397 Attempts)		
	Before Intervention (%)	After Intervention (%)	Follow-up (%)
Overall successful cannulation	12	32	26
Normal ventricles	27	35	28
Shifted ventricles	10	19	19
Compressed ventricles	10	42	31
Ipsilateral placement	76	60	77

These numbers differ slightly from the text because these are raw unadjusted proportions and not proportions adjusted for covariates.

1.24–5.41; P = 0.011), but performance at follow-up was significantly worse than immediately after intervention (P < 0.001). Shifted brains were significantly more difficult than normal brains (OR, 0.16; 95% CI, 0.06–0.44; P < 0.001), but compressed brains were not (OR, 0.43; 95% CI, 0.17–1.10; P = 0.08). Terms for year in training and year squared were significant (P < 0.001 and P = 0.001, respectively). The best performance was achieved by PGY3 and PGY4 residents (adjusted probability of success, 44% and 45%, respectively), and performance was lower for both more junior residents (success rate, 8% for PGY1 and 25% for PGY2) and more senior residents (success rate, 19% for PGY5 and 23% for PGY6+). Attempt number (P = 0.30) and the number of ventriculostomies performed in the last 12 months (P = 0.16) were not significantly associated with success.

There were significant effects of time, brain type, and individual brain within type on ipsilateral versus contralateral results. The overall adjusted probability of an ipsilateral placement was 71% before intervention, 56% after intervention, and 69% at follow-up. Relative to preintervention performance, residents were less likely to produce an ipsilateral placement immediately after intervention (OR, 0.34; 95% CI, 0.19–0.63; P < 0.001) but not so at follow-up (OR, 0.85; 95% CI, 0.42–1.69; P = 0.63). More senior residents were less likely to have an ipsilateral placement (OR, 0.77; 95% CI, 0.61–0.96; P = 0.02). Greater catheter depth was associated with lower likelihood of ipsilateral placement (r = −0.35, P < 0.001). Attempt number (P = 0.29) and the number of ventriculostomies in the last 12 months (P = 0.35) were not significant predictors.

Finally, there were significant effects of attempt number, brain type, and individual brain on catheter depth but no significant effect of time. Mean (SE) catheter depth on the first attempt was 5.30 (0.13) cm. Residents increased catheter depth by a mean of 0.14 cm at each additional attempt (P = 0.013) and had greater mean (SE) depths for compressed brains [1.94 (0.44) cm deeper; P < 0.001] and shifted [1.89 (0.44) cm deeper; P < 0.001] relative to normal brains. Time (P = 0.09), resident year in program (P = 0.60), and the number of ventriculostomies in the last 12 months (P = 0.83) were not significant predictors of catheter depth.

Only individual brain within brain type was a significant predictor of distance to the FOM for successful attempts (P < 0.001).

Field (Live Surgery) Data

Twenty-three residents provided field data. Seven residents who provided preintervention field data graduated, left their residency program or were otherwise unavailable, and did not participate in the practice sessions.

Of the 16 residents who participated in simulator practice, 12 provided live surgery data; they reported a total of 138 ventriculostomy procedures, 91 before training and 47 after training, with at most 37 surgeries per resident. Overall, 103 surgeries involved normal ventricles, 21 involved shifted ventricles, 12 involved compressed ventricles, 1 involved a ventricle that was both shifted and compressed, and the ventricles of 1 patient were not described. The distribution (case mix) of ventricle types did not vary significantly before and after intervention: χ^2 = 0.96, df = 2, P = 0.62 (Table 2).

Cannulation was (eventually) successful in all but 3 of these surgeries, and thus, success of cannulation could not be modeled. Cannulation succeeded on the first attempt in 119 surgeries (86%). There was a positive effect of simulator practice on the likelihood of succeeding on the first attempt, 82% before training versus 94% after training (OR, 4.74; 95% CI, 1.10–20.4; P = 0.04).

There were no effects of simulator practice on whether the catheter was ipsilateral (89% of the time) or contralateral (P = 0.23) or on catheter depth (P = 0.32). Hemorrhages occurred in 9 surgeries (7%) and were not predicted by simulator practice. The catheter entered the intended space of the lateral ventricle (as opposed to the third ventricle or other space) 59% of the time and was significantly more likely to have entered the lateral ventricle (as opposed to the third ventricle) before versus after practice (OR, 2.61; 95% CI, 1.20–5.77; P = 0.02) (Table 3).

Program Evaluation: Resident Feedback

Table 4 shows the results of the resident surveys. Residents found the images and the sensation when puncturing the ventricle to be realistic: image realism range, 2 to 4 of 5; mode 3; mean (SD), 2.9 (8.0); and sensation realism range, 1 to 4 of 5; mode 3; mean (SD), 2.8 (0.94). Residents' comments regarding the "best features" of the simulator focused on the 3D visualization and haptic feedback. The primary recommendation for improvement was to be able to select the location for burr hole placement. Residents also suggested that the simulator should be able to display landmark planes to assist in learning to aim the probe. Residents noted that the simulator sometimes reported the catheter tip just beyond the ventricle when, visually, it appeared to be in the ventricle; this position would have been clinically effective because the fluid collection openings are just behind the tip. Several residents noted that the simulator differed from actual practice in that, in practice, to avoid injury, the catheter stylet would be advanced only until the ventricle is entered, then the catheter soft-passed further into the ventricle toward the FOM; 1 resident expressed concern that aiming for the FOM with the simulator probe might encourage overly deep penetration of the ventricle with the stylet.

Of the 16 participants, 15 (94%) completed the post-practice evaluation survey questionnaire; responses are shown in Table 4. Most residents felt that practice on the simulator was at least somewhat helpful in improving their ability to perform the different elements of the procedures

TABLE 2. Resident Performance in Live Surgery by Level of Training

	Proportion of Reported Successful Cannulation on the First Attempt (Unadjusted)				
	PGY1 (n = 3)	PGY2 (n = 4)	PGY3 (n = 1)	PGY4 (n = 3)	PGY7 (n = 1)
Before intervention, n (%)	12/15 (80)	40/51 (78.4)	1/2 (50)	21/22 (95)	1/1 (100)
After intervention, n (%)	22/24 (92)	17/18 (94)	5/5 (100)	No live surgery reported	No live surgery reported

TABLE 3. Resident Performance in Live Surgery Before and After Intervention (Unadjusted)

	Before Intervention (91 Procedures)	After Intervention (47 Procedures)
Cannulation on the first attempt, n (%)	75/91 (82)	44 (94)
Ipsilateral placement, n (%)	76/89 (85)	44 (94)
Lateral ventricle placement, n (%)	61/91 (67)	21 (45)
Hemorrhages, n (%)	6/91 (7)	3 (6)
Depth of catheter insertion, mean (SD) (cm)	6.28 (0.40)	6.39 (0.55)

on live patients. Residents thought that practice on the simulator would be "very helpful" for introducing novice residents to the procedure before performing it on live patients.

DISCUSSION

This study describes the development and implementation of a library of virtual brains for use with a virtual reality/haptic simulator to provide practice in ventriculostomy. Uniquely, the library provided a range of normal and abnormal anatomic variations and difficulty levels to facilitate deliberate practice and the acquisition and transfer of skills, a recommended best practice for simulation-based education.[9]

Both simulation-based and live procedure outcome measures showed significant improvement after practice, demonstrating that skills obtained on the simulator could be transferred to the surgical setting. After participating in the simulator practice session, residents were more likely to successfully cannulate the ventricle on the first pass in live surgery, an important patient safety outcome that could decrease the risk of complications such as hemorrhage and infection, although this was not seen in our small-cohort study. Performance improvement may have reflected a combination of factors including residents' better ability to translate the 2-dimensional CT scan images into a 3D visualization of the ventricles in the brain, better estimates of the direction and distance to the ventricle, and increased sensitivity to the tactile sensation of the transition between brain parenchyma and the ventricle.

Residents felt that the simulator would be most helpful for novice residents. Resident performance on the simulator was consistent with the "learning curve" findings reported by Banerjee et al[10]; intermediate-level residents, who perform the bulk of the live procedures in the hospital, outperformed novices and more experienced residents who are no longer routinely performing the procedure. The number of procedures performed in the past 12 months did not predict performance once the model controlled for year in training, perhaps reflecting a time lag in both learning and decay: first- and second-year residents who perform many procedures have not yet gained proficiency in the procedures, and fourth-year residents who are no longer performing many ventriculostomies have not yet lost their skill. Although practice on the virtual library may have accelerated the learning curve for novices, we lacked data to demonstrate a resurgence of lapsed skills in more senior residents.

When validating a simulator, it is essential to explore the possibility of inadvertently inculcating undesirable behaviors. After intervention, residents were more likely to generate contralateral placement in the simulator and placement in the third ventricle on live surgery, reflecting a tendency for deeper and more medial placement of the probe after practice. The reason for this tendency is unclear and requires further study; it may be related to the inability to "soft pass" the inner flexible catheter after insertion of the rigid stylet. (Whereas no significant increase in catheter depth was seen in live procedures, this likely reflects inexact estimation of depth to the nearest 0.5 cm.) Deeper insertion and contralateral or third-ventricle placement may increase the likelihood of complications such as hemorrhage. A modification of the simulator to emulate "soft passage" of the catheter after entering the ventricle could prevent this undesired effect.

The effectiveness of simulator practice could be improved by both simulator and curriculum changes. The new Generation II ImmersiveTouch ventriculostomy simulator

TABLE 4. Resident Survey Responses*

	Immediately After Practice (n = 15)			Follow-up Survey (n = 12)		
	To What Extent Do You Think That Practicing on the Virtual Brains Improved Your…?			To What Extent Do You Think That Practicing on the Virtual Brains Improved Your Skills in Actual Surgery?		
	Range	Mode	Mean (SD)	Range	Mode	Mean (SD)
1. Ability to use the CT scan to aid in estimating the location of the ventricle	1–5	3	2.7 (1.2)	1–5	3	3.0 (1.0)
2. Ability to aim the probe toward the ventricle	1–5	2	2.8 (1.4)	1–5	3	2.9 (1.1)
3. Ability to sense the pressure change when entering the ventricle	1–5	3	3.0 (1.4)	1–5	3	3.2 (1.2)
4. Ability to estimate how far the catheter should be advanced within the ventricle	1–5	4	2.8 (1.3)	1–5	3	2.9 (1.2)
5. Overall ability to perform a ventriculostomy on a live patient	1–5	3	2.8 (1.1)	1–5	2	2.8 (1.0)
6. Overall, how satisfied were you with this practice session?	1–5	3	3.4 (1.1)			
7. How useful would this practice be for a new resident before performing live ventriculostomies? (n = 10 responses)				1–5	4	3.8 (1.1)

*1 = not at all; 2 = somewhat; 3 = improved, satisfied, or useful; 4 = very; 5 = extremely.

allows residents to determine burr hole placement. Other recommendations include providing landmark planes to assist novices in learning proper orientation of the catheter, simulating draping of the head to remove visual cues for more advanced residents, ensuring that placement feedback is based on clinically relevant markers such as the position of the section just behind the catheter tip, and emulating soft passage of the catheter in the ventricle as described previously. Curricular improvements include guiding residents to systematically explore the anatomy of the ventricles, scheduling multiple shorter practice sessions to avoid fatigue and reinforce learning, and establishing mastery criteria and goals.

Limitations of the study include a relatively small number of residents representing 4 residency programs from a single metropolitan area. Studies of live outcome data could ensure more complete data captured by providing external observers in situ.

Previous validation studies of the Immersive Touch simulator using a single simulated brain with normal ventricles established that the mean distance of the catheter tip from the FOM in the simulator closely approximated that obtained in live surgical procedures and that midlevel residents performed better than either novices or senior residents.[10–12] The present study moves beyond these studies by developing the extended library of 15 virtual brains and assessing the impact of simulator practice on both simulator and live surgery outcomes. Future studies include developing a structured curriculum to optimally accelerate the learning of novice residents, analyzing the impact of simulator practice on component tasks of the procedure, and exploring the impact of just-in-time simulator training on nonneurosurgeons who must perform the procedure in emergencies.

CONCLUSIONS AND SIGNIFICANCE

Practice on a virtual reality/haptic simulator improved performance in neurosurgery residents as measured by simulator and live procedure outcomes and resident self-report. A library of virtual brains provided a range of normal and abnormal anatomies, facilitating deliberate practice and successful transfer of skills to live surgical procedures; virtual libraries should be explored for other procedures as well. Simulator practice, especially by novice residents, may accelerate learning and shorten the learning curve for this common procedure and thereby decrease morbidity and complications due to inexpert technique.

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