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Accuracy of routine external ventricular drain placement following a mixed reality–guided twist-drill craniostomy

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OBJECTIVE The traditional freehand placement of an external ventricular drain (EVD) relies on empirical craniometric landmarks to guide the craniostomy and subsequent passage of the EVD catheter. The diameter and trajectory of the craniostomy physically limit the possible trajectories that can be achieved during the passage of the catheter. In this study, the authors implemented a mixed reality–guided craniostomy procedure to evaluate the benefit of an optimally drilled craniostomy to the accurate placement of the catheter.

METHODS Optical marker–based tracking using an OptiTrack system was used to register the brain ventricular hologram and drilling guidance for craniostomy using a HoloLens 2 mixed reality headset. A patient-specific 3D-printed skull phantom embedded with intracranial camera sensors was developed to automatically calculate the EVD accuracy for evaluation. User trials consisted of one blind and one mixed reality–assisted craniostomy followed by a routine, unguided EVD catheter placement for each of two different drill bit sizes.

RESULTS A total of 49 participants were included in the study (mean age 23.4 years, 59.2% female). The mean distance from the catheter target improved from 18.6 ± 12.5 mm to 12.7 ± 11.3 mm ($p = 0.0008$) using mixed reality guidance for trials with a large drill bit and from 19.3 ± 12.7 mm to 10.1 ± 8.4 mm with a small drill bit ($p < 0.0001$). Accuracy using mixed reality was improved using a smaller diameter drill bit compared with a larger bit ($p = 0.039$). Overall, the majority of the participants were positive about the helpfulness of mixed reality guidance and the overall mixed reality experience.

CONCLUSIONS Appropriate indications and use cases for the application of mixed reality guidance to neurosurgical procedures remain an area of active inquiry. While prior studies have demonstrated the benefit of mixed reality–guided catheter placement using predrilled craniostomies, the authors demonstrate that real-time quantitative and visual feedback of a mixed reality–guided craniostomy procedure can independently improve procedural accuracy and represents an important tool for trainee education and eventual clinical implementation.

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KEYWORDS external ventricular drainage; craniostomy; mixed reality; image-guided surgery; HoloLens

Technological advancements continue to transform the landscape of medicine, improving patient outcomes across a wide range of medical disciplines; neurosurgery is no exception to this trend. Real-time, image-based guidance systems, such as neuronavigation technologies, are a prime example of this.[1] These innovations allow neurosurgeons to perform precision work with limited surgical exposures, such as in keyhole craniotomies, minimally invasive spine surgery, and endoscopic procedures.[2,3] An exciting development in image-based guidance within neurosurgery is the implementation of mixed reality.[4–12] By incorporating real-world visuals with real-time digital information, mixed reality facilitates the evaluation of patient-specific anatomy and surgical decision-making in the absence of a direct line of sight. An active area of study for our laboratory and others is the use

ABBREVIATIONS EVD = external ventricular drain.

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of mixed reality to assist in the placement of an external ventricular drain (EVD), one of the most frequently performed neurosurgical procedures.[13–17]

Traditionally, surgeons place EVDs using the theoretical relationship between ventricular anatomy and external anatomical landmarks. The trajectory is approximated by Kocher's point and the intersection of the planes created by the ipsilateral medial canthus and the tragus, with empirical adjustments made using information from preprocedural imaging. Although EVD insertion is relatively common, occurring more than 20,000 times annually in the United States alone, misplacement may result in undue brain tissue trauma as well as delayed relief of intracranial hypertension.[18] The goal of visual guidance during EVD insertion, therefore, is to increase single-pass accuracy and minimize the morbidity associated with the procedure.[19]

Previous mixed reality–assisted EVD studies have tracked only the ventricular catheter/stylet system to improve placement accuracy.[13–17,20,21] Several studies, including ours,[13,20,21] used a predrilled craniostomy through which the user would guide the catheter to the target. Other studies[15,16] projected a static hologram that suggests the entry point at Kocher's point for craniostomy. Drilling is a technically challenging portion of the procedure, subject to skiving and misdirection. However, it must be performed with the same accuracy as intended for the trajectory of the catheter, since the craniostomy must facilitate the intended trajectory of the catheter from the cranium to the target, typically the foramen of Monro.[22]

We hypothesized that navigation-assisted cranial access could improve the accuracy of subsequent catheter placement. To this end, we developed a mixed reality technology to aid with the craniostomy portion of the EVD procedure and performed user studies to assess the accuracy of catheter placement during blind and mixed reality–guided procedures in a large cohort of nonprofessional trainees. We further hypothesized that a smaller craniostomy diameter drilled in an accurate trajectory would decrease the potential deviation of the catheter from the target. Therefore, we performed the user studies with a standard-sized drill bit similar to those found in common cranial access kits, and a smaller drill bit that was closer to the outer catheter diameter.

Methods

Optical Marker–Based Image Registration

To achieve robust and precise image registration, optical markers were used to track the hand-twist drill and the skull phantom to overlay the textual guidance and brain ventricular hologram in mixed reality. Six Flex 3 OptiTrack cameras (NaturalPoint) with lens specifications of 57.5° in the field of view were used for real-time optical tracking. An anonymized high-resolution CT scan was obtained from an anonymous patient for segmentation of the skull and cerebral ventricles using 3D Slicer software.[23] The skull model was 3D printed using polylactic acid filament, and the brain ventricular model was imported into Unity (Unity Technologies) to be visualized as a hologram in mixed reality. Five and eight optical markers were attached to the hand-twist drill and the skull phantom, respectively, and evenly distributed for real-time tracking (Fig. 1A). These two tracking models were registered to the OptiTrack system during the camera calibration process for continuously tracking and streaming the changes in position and orientation data to HoloLens 2 (Microsoft) to be displayed as holograms. Because of the different coordinate systems between the OptiTrack and HoloLens 2, a single fiducial marker was used as a localization marker with Vuforia marker detection to compute the transformation of coordinates. This allows the HoloLens 2 to use the position and orientation data of tracked models from OptiTrack to be correctly overlaid in the mixed reality view. The robustness of this optical tracking–based image registration has been shown in previous studies.[20,21]

Sensing-Integrated Skull Phantom

To provide instantaneous assessment and avoid the need for CT-based imaging of the catheter placement performed in prior user studies, a custom intracranial mold was created with two camera sensors oriented in the coronal and sagittal views to capture the catheter tip and a steel ball representative of the phantom-specific foramen of Monro (Fig. 1B). A Raspberry Pi 4B microcontroller (Raspberry Pi) was used to capture image frames and programmed to calculate 3D coordinates of the catheter tip and steel ball as well as calculate the linear difference between the two (Fig. 1C). The inside of the mold was filled with a transparent 8% gelatin solution to simulate brain parenchyma and hold the catheter tip in place for analysis.[24]

Participants and Procedures

The study was approved by our institution's institutional review board. We recruited participants from local universities and medical schools in our metropolitan area. Following consent, the participants filled out a pre-experiment questionnaire and watched an instructional video about the freehand EVD procedure. Participants who reported red-green colorblindness or were unable to complete all user trials were excluded from the study analysis. Eye calibration on the HoloLens 2 was performed to ensure robust image registration of holograms and tracking of participants' eye gaze data. A craniostomy was performed within a 2-cm radius encompassing Kocher's point using a twist drill obtained from the Codman Cranial Access Kit (Integra), with 5.2-mm (large) and 3.6-mm (small) drill bits (Dewalt), which were modified to be the same length. The order of the drill bits used in the trials was randomized in the study. Participants first performed a blind EVD trial without wearing the HoloLens 2 headset. During the blind procedure, participants were instructed to drill in a trajectory intersecting the ipsilateral medial canthus and tragus. In the mixed reality–guided procedure, the degrees of deviation from the optimal trajectory to the foramen of Monro in both the sagittal and coronal axes were displayed in an offset view from the drill in the mixed reality hologram (Fig. 1D). Additionally, when the deviation was less than 1° in each plane, the hologram projection of the twist drill trajectory changed from red to green (Fig. 1E). Next, a Codman Bactiseal EVD catheter (Integra) with a 3.4-mm outer diameter was passed through

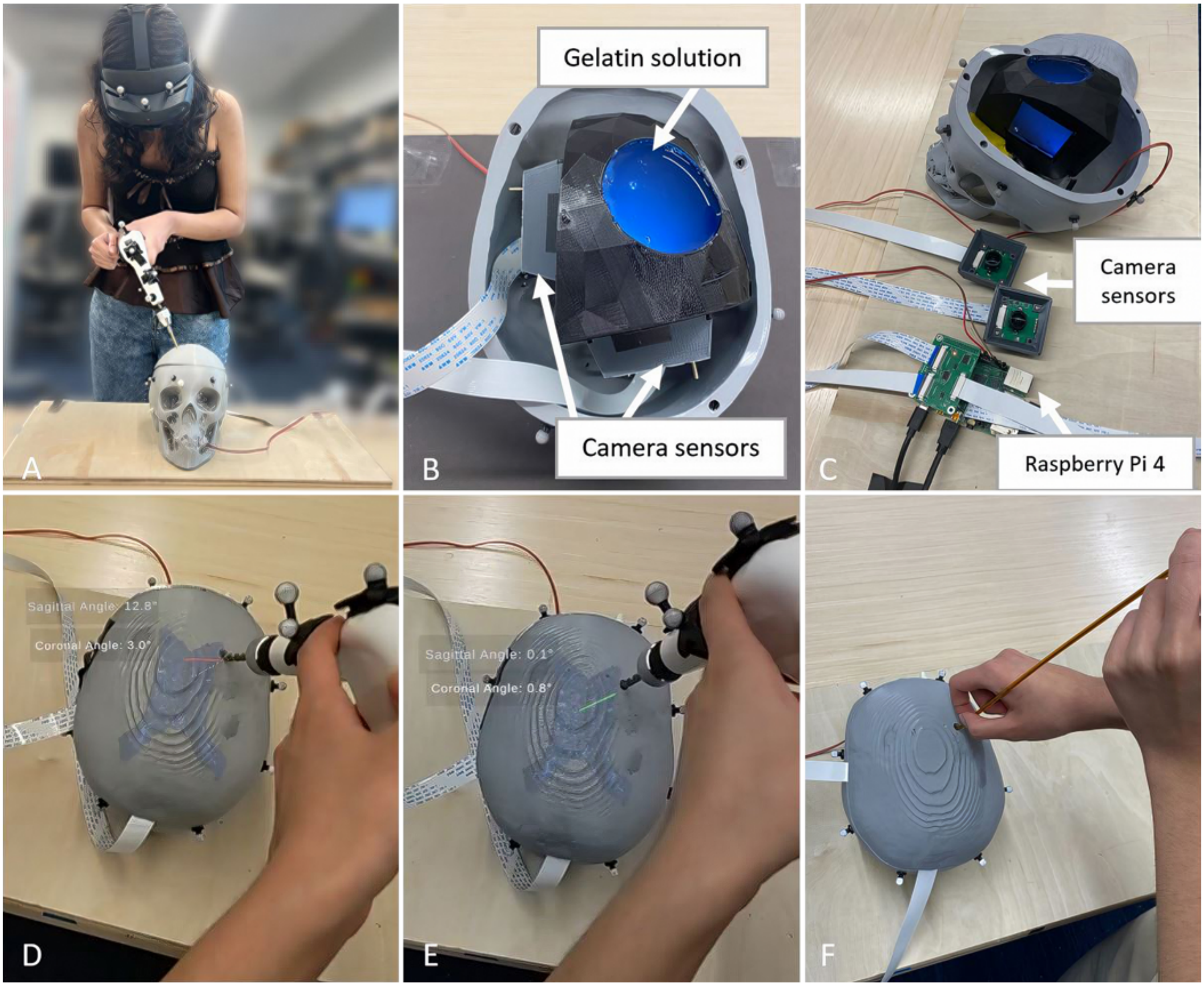

FIG. 1. Sensing-integrated skull phantom for mixed reality–guided craniostomy. **A:** A sensing-integrated skull phantom for optical marker–based tracking of the twist-drill and mixed reality overlay of ventricular anatomy was created. **B and C:** The intracranial phantom mold was filled with 8% gelatin (B), and ventriculostomy catheter placement was tracked via camera sensors integrated into Raspberry Pi 4 microcontrollers (C). **D:** Drill trajectories were overlaid onto the phantom in *red* with degrees of deviation from the optimal trajectory in the coronal and sagittal planes displayed. **E:** When the trajectory was < 1° from optimal, the holographic trajectory changed to *green*. **F:** Following the mixed reality–guided craniostomy, the ventriculostomy catheter was advanced.

the craniostomy (Fig. 1F). In all trials, the depth to target, calculated from the sensors inside the skull phantom, was reported to the participant for both the blind and mixed reality procedures to control for this as a source of variability. The user was responsible for measuring this depth on the catheter and instructed not to advance beyond that point. In all trials, the user was instructed to pass the catheter in a trajectory intersecting the ipsilateral medial canthus and tragus. Following the procedure, structured and open-ended feedback was collected from participants via a written postsurvey (Fig. 2).

Evaluation

For all blind and mixed reality–assisted EVD trials, the depth of catheter placement, EVD accuracy, and duration of drilling and catheter insertion were recorded. The recommended catheter depth was calculated as the distance from the location of the drilled entry point to the phantom's representative foramen of Monro. In addition, EVD placement accuracy was measured as a distance from the tip of the catheter to the target point of the foramen of Monro inside the skull phantom as described above. The time of drilling was recorded from the moment the participant started drilling an entry point on the skull phantom until the drilling procedure was complete. The time of catheter insertion was recorded from the moment the participant started inserting the catheter through the drilled entry point until the moment the participant removed the metal stylet from the catheter. Both time measurements were recorded using a stopwatch.

Statistical Analysis

Continuous variables were summarized with means and standard deviations. Categorical variables were summarized as counts and percentages. Statistical comparisons for individual user trial data were performed using a paired Student two-tailed t-test. Comparisons between different user groups were made with an unpaired Student t-test assuming equal variance. Significance was set at $p < 0.05$. All statistical analyses were two-sided. All analyses and visualizations were performed in Prism version 10.0 (GraphPad).

Results

Theoretical Craniostomy Relationships

To begin, we derived the mathematical relationship between the craniostomy diameter, bone thickness, catheter outer diameter, catheter length, and maximum potential deviation from the intended target of the catheter with the simplified equation and schematic depicted in Fig. 3. To visualize the impact of the difference between the craniostomy diameter and the catheter diameter, we defined the term "delta" as craniostomy diameter – catheter outer diameter and plotted the maximum potential deviation as a function of delta. Plots of varying catheter depths (Fig. 4A) and bone thicknesses (Fig. 4B) are presented. As expected, the larger the difference between the craniostomy and catheter diameters (i.e., delta), the larger the maximum potential for deviation from the target. Deeper catheter placement increases this deviation, while thicker bone decreases the potential for deviation.

We hypothesized that drilling in a more accurate trajectory using mixed reality guidance would improve subsequent catheter accuracy compared with a traditional "blind" craniostomy. Furthermore, we hypothesized that decreasing the delta by performing the guided craniostomy with a smaller 3.6 mm drill bit (delta = 0.2 mm) compared with a traditionally sized 5.2-mm drill bit (delta = 1.8 mm) would further improve this accuracy. To test these hypotheses, we conducted user studies as described in *Methods* with the following results.

User Study Participant Demographics

Fifty-two participants were recruited from universities in the local area, with two participants excluded from the study because of technical failure during their trials and one participant excluded due to red-green colorblindness. A total of 49 participants between the ages of 20 and 35 years (mean 23.4 ± 2.4 years) composed the final study cohort (Table 1). Twenty-nine (59.2%) participants identified as female. The participants were composed of 15 (30.6%) nonmedical individuals and 34 (69.4%) medical students. A total of 196 EVD placement trials were conducted. Thirty (61.2%) participants wore glasses, and 2 (4.1%) participants reported having other unspecified eyesight-related conditions. Twenty-four (49%) participants had at least one prior experience using mixed reality. Participants were asked to rate their understanding of the craniostomy's purpose and anatomy from 1 (least knowledgeable) to 9 (most knowledgeable). The mean scores were 4.29 ± 2.69 and 1.79 ± 1.27 for medical students and 4.27 ± 2.71 and 2.33 ± 1.72 for nonmedical students, respectively.

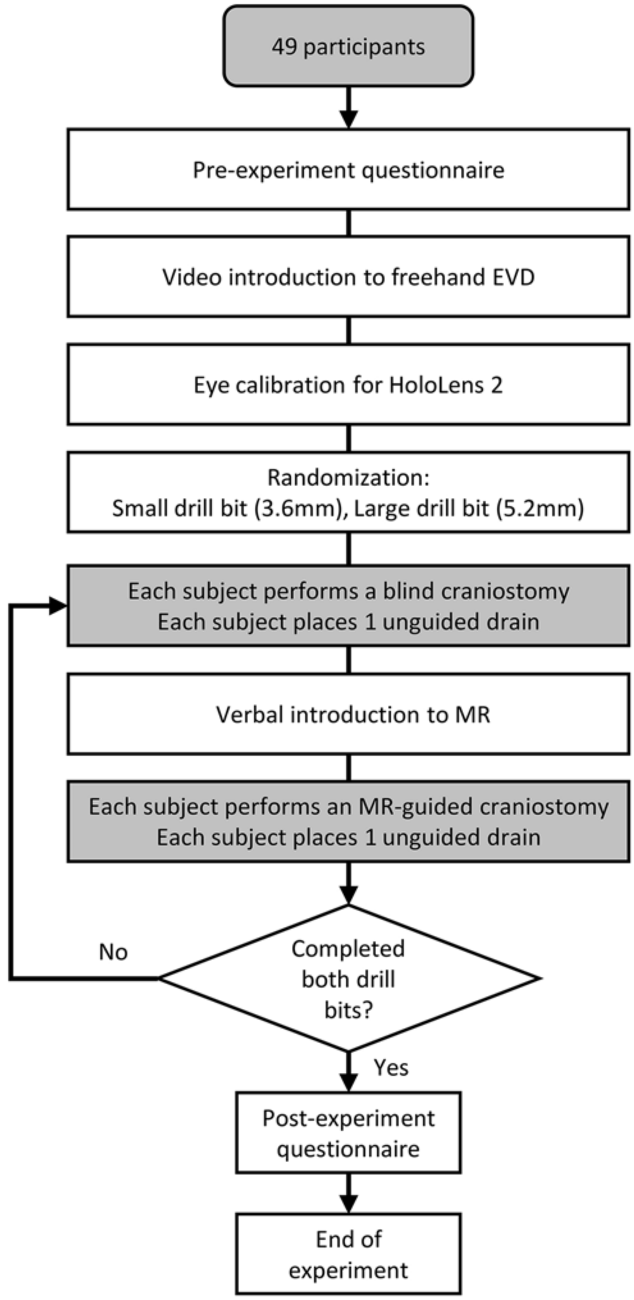

FIG. 2. Flow diagram for the user study described in *Methods*. MR = mixed reality.

EVD Accuracy

Mixed reality–guided craniostomy improved catheter accuracy across the entire study cohort compared with blind (unguided) placement with both the 5.2-mm (large) and 3.6-mm (small) drill bits. The mean catheter placement accuracy improved from 18.6 ± 12.5 mm to 12.7 ±

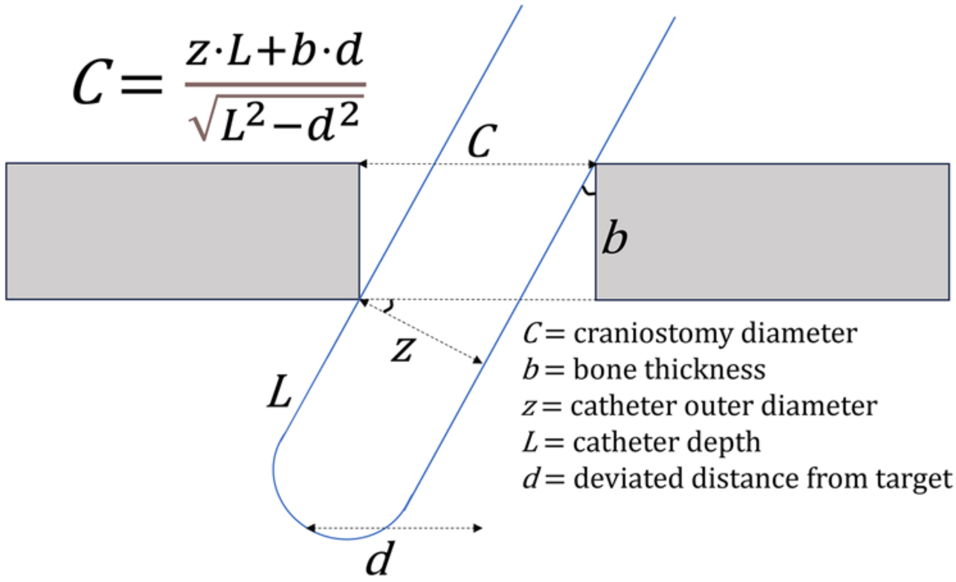

FIG. 3. Relationship between craniostomy diameter, bone thickness, and catheter dimensions to potential catheter deviation. Mathematical equation and schematic of the relationship between bone, craniostomy, and catheter specific dimensions affecting the maximal potential malposition of the EVD catheter from the center point of the craniostomy.

11.3 mm for trials with the large drill bit (p = 0.0008), while the mean accuracy improved from 19.3 ± 12.7 mm to 10.1 mm ± 8.4 mm with the small drill bit (p < 0.0001) (Fig. 5A and Table 2). Comparison of the mixed reality–guided craniotomies using the different-sized bits revealed a statistically significantly higher accuracy for the smaller bit (10.1 mm ± 8.4 mm) than for the larger one (12.7 ± 11.3 mm) (p = 0.0393).

Analyses of medical student and non–medical student subgroups demonstrated improvement of the medical students between blind and mixed reality–guided trials compared with non–medical students. The medical students improved their catheter placement accuracy by a mean of 7.3 ± 11.3 mm with the large drill bit, compared with a mean improvement of 2.8 ± 11.8 mm for the non–medical students. Similarly, medical students improved their accuracy by mean of 10.8 ± 14.1 mm with the small drill bit, compared with an average of 5.8 ± 8.9 mm for non–medical students. The comparisons between the improvements for both drill bit sizes were not statistically significant.

We compared participants' levels of prior mixed reality experience to evaluate whether they influenced their accuracy with the procedure. On average, the participants who had used mixed reality at least once prior to the experiment improved their accuracies by 6.1 ± 13.5 mm using the large drill bit and by 10.5 ± 13.7 mm using the small drill bit. The participants without prior experience improved their accuracies by 5.7 ± 9.7 mm and 8.0 ± 12.2 mm, respectively. The comparisons between the improvements for both drill bit sizes were not statistically significant.

Drilling and Insertion Time Results

Additional information regarding the catheter depth, drilling and insertion times are listed in Table 2. Drilling times were significantly longer using mixed reality guidance, although drilling with the smaller drill bit took significantly less time than drilling with the larger bit (Fig. 5B). Catheter depths were not significantly different between groups, and insertion times, while shorter in the mixed reality trials, were only significant for the blind versus mixed reality groups using the small drill bit (Fig. 5B).

Survey Response

For the analysis of the survey response, the positivity rate, defined as the percentage of participants who responded "agree" or "strongly agree" to the question, was calculated (Fig. 6). With respect to the guidance aspect of the mixed reality system, most participants agreed that the mixed reality guidance was helpful in performing the craniostomy procedure. Participants found both the textual and visual guidance helpful, with positivity rates of 69.4% and 91.8%, respectively. When asked if the textual and visual guidance were accurate, participants answered with positivity rates of 61.2% and 67.4%, respectively.

Furthermore, most of the participants were positive regarding the overall mixed reality experience in their survey responses. Overall, 71.4% of users agreed that the mixed reality system was "easy to use." Participants found the projected drill trajectory and the optimal trajectory to be accurate, answering with positivity rates of 79.6% and 73.5%, respectively. Overall, 73.5% of participants agreed that the different structures in the ventricle were easily distinguished from one another.

When asked about the educational and clinical applications of the mixed reality system, 90.7% of participants agreed that the mixed reality system would be helpful for training medical students and residents in performing a craniostomy.

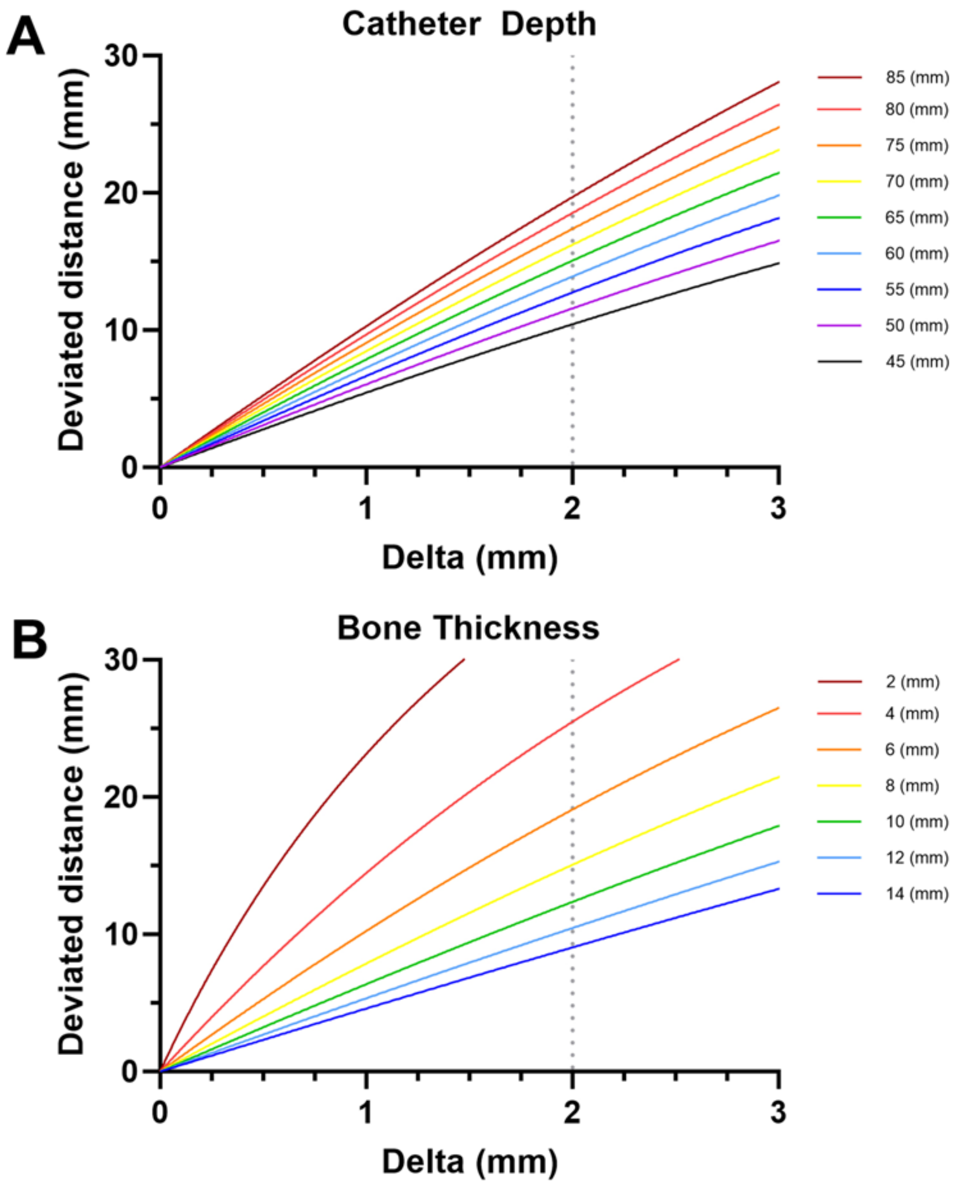

FIG. 4. Effect of catheter depth and bone thickness on deviated distance as a function of the difference between the craniotomy diameter and the catheter diameter (delta). Plots derived from the equation in Fig. 3 were generated as a function of the delta term. A catheter diameter of 3.4 mm was assumed for both plots, while a bone thickness of 8 mm was assumed for the various depths (**A**) and a catheter depth of 75 mm was assumed for various bone thicknesses (**B**). A *vertical dashed line* at 2.0 mm is plotted, representing the delta of a standard Codman twist-drill bit (5.4 mm) and Bactiseal EVD catheter (3.4 mm).

Open-Ended Feedback

In the survey's open-ended feedback, 11 participants remarked that the mixed reality holograms were helpful in planning out their drilling trajectories. Three participants described the color-changing mechanic of the drill trajectory to be helpful. Three participants described the system as "intuitive," 4 found it "easy to understand/use/follow," 1 described it as "user-friendly," 1 as "unambiguous," and 2 as "straightforward." Many participants expressed optimism about the system, describing the overall mixed reality experience as "interesting" (2 participants), "fun" (2 participants), "exciting" (1 participant), "cool" (5 participants), "enjoyable" (2 participants), "pleasant" (1 participant), and having "a lot of potential" (1 participant). Many participants commented on the challenge of the actual drilling process. Six participants described that the overall drilling procedure was difficult, and 7 found it to be uncomfortable.

Discussion

Craniostomy Accuracy

The placement of an EVD is the primary means by which a neurosurgeon may quickly relieve elevated in-

TABLE 1. Participant demographics

Demographics	Non–Medical Students (n = 15)	Medical Students (n = 34)
Mean age (range), yrs	23.3 (20–35)	23.5 (22–27)
Sex, n (%)		
M	11 (73.3)	9 (26.5)
F	4 (26.7)	25 (73.5)
Education, n (%)		
Undergraduate	6 (40)	
Graduate	6 (40)	
Other	3 (20)	
1st-yr medical school		32 (94.1)
2nd- to 4th-yr medical school		2 (5.9)
Experience w/ MR, n (%)		
Never	5 (33.3)	20 (58.8)
Once or twice	6 (40)	13 (38.2)
Infrequently	2 (13.3)	1 (2.9)
Frequently	2 (13.3)	0 (0)
Understanding of craniostomy, mean ± SD*		
Purpose	4.27 ± 2.71	4.29 ± 2.69
Anatomy	2.33 ± 1.72	1.79 ± 1.27

MR = mixed reality.
* Based on a scale from 1 (least knowledgeable) to 9 (most knowledgeable).

tracranial pressure and guide ongoing medical treatment through continued pressure monitoring.[1] A neurosurgical resident's EVD training experience is often done through bedside teaching from senior residents, and proficiency is gained through repeated procedures.[25] In the senior author's experience, the twist-drill craniostomy is one of the most challenging portions of the procedure due to the physicality of the drilling process and the rigor of maintaining the empirical trajectory while drilling.[22] Ideally, the trajectory of the craniostomy must align with the intended trajectory of the catheter. To this end, a poorly directed craniostomy cannot be overcome by a correctly oriented catheter due to the nature of a rigid bone and flexible catheter. Anecdotally, multiple failed attempts at catheter placement are frequently remedied by performing the craniostomy step again. We illustrate in Figs. 3 and 4 the physical parameters, including bone thickness, craniostomy diameter and catheter diameter that constrain the possible trajectories. Even with a craniostomy perfectly aligned toward the target, the potential deviation from the target is increased with thinner bone, longer catheter depths, and larger differences between the catheter and craniostomy diameters, termed "delta" in this study. The relationship derived in Fig. 3 can be more broadly applied to keyhole surgeries to define the limitations of the craniotomy diameter as related to the depth and radius of the operative lesion and the diameter of the operating instrument.

We proposed the current study to demonstrate the benefit of an accurately performed craniostomy and the utility of mixed reality to enable this. We found that users naive

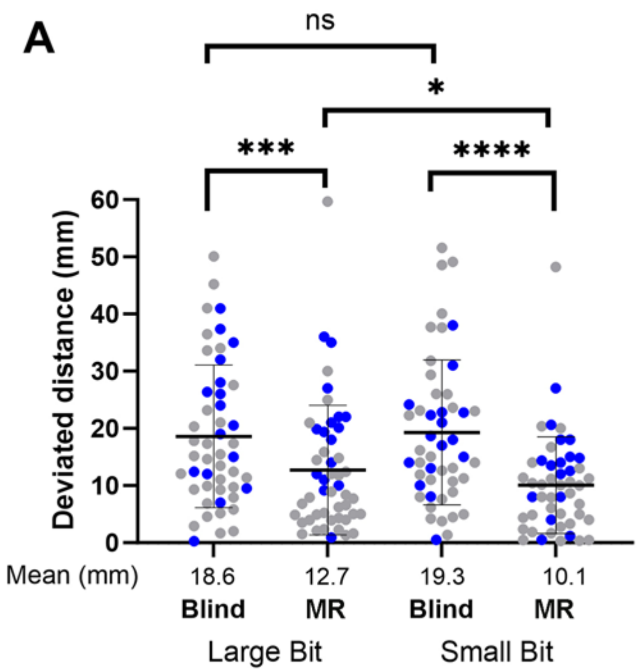

FIG. 5. Guided craniostomy user study results. Individual data points for each user study result reporting deviate distance from the target (**A**) or drilling time (**B**) were plotted with medical students in *gray* and nonmedical students in *blue*. Means with standard deviation are shown. *p < 0.05; **p < 0.01; ***p < 0.001; ****p < 0.0001; ns = not significant. Statistical comparisons were made using the Student paired t-test.

to the EVD procedure improved their catheter placements solely by creating a more accurately directed craniostomy using mixed reality.

We additionally tested the hypothesis that an accurately drilled small diameter craniostomy closely matching the diameter of the catheter would create less opportunity for catheter deviation due to the smaller delta and found a

TABLE 2. Quantitative performance of guided craniostomy

	Large Bit (5.2 mm)			Small Bit (3.6 mm)			Large vs Small p Value	
	Blind	MR-Guided	p Value	Blind	MR-Guided	p Value	Blind vs Blind	MR vs MR
Mean deviation from target, mm	18.6 ± 12.5	12.7 ± 11.3	0.0008	19.3 ± 12.7	10.1 ± 8.4	<0.0001	0.7435	0.0393
Mean suggested depth, mm	75.1 ± 5.4	74.4 ± 4.7	0.4757	74.1 ± 5.8	73.7 ± 5.4	0.7130	0.2772	0.5119
Mean drilling time, sec	109.6 ± 76.7	191.2 ± 115.2	<0.0001	63.9 ± 40.2	145.2 ± 91.0	<0.0001	0.0004	0.0027
Mean catheter insertion time, sec	12.4 ± 9.9	10.3 ± 6.5	0.1786	14.4 ± 10.8	10.4 ± 5.2	0.0086	0.3378	0.9612

small but significant improvement in the accuracy (from 12.7 to 10.1 mm). From our theoretical model in Fig. 3, we predicted an improvement in the maximum potential deviation from target of 16 mm to 2 mm from the large to small bits respectively, assuming a catheter depth of 75 mm and bone thickness of 8 mm for our specific phantom. We suggest that there are physical limitations to the real-world scenario of guiding a hand drill, which can be difficult to stabilize in the hands of a new user and so in this situation, using a smaller drill bit may not provide additional benefit. However, we do see this principle as useful for rigidly drilled craniostomies, such as those performed in a frame or rigid arm during stereotactic biopsy.

The majority of participants in our study were medical students (69.4%) in their 1st year of training. Analysis of the improvement with mixed reality between medical and nonmedical participants did not reveal significant differences. Medical students also rated their a priori understanding of the anatomy and purpose of the EVD procedure similarly to non–medical students, suggesting a more limited role for experience in this early career cohort.

Subjectively, participants found the mixed reality guidance to be helpful in learning and understanding the procedure. The mixed reality guidance improved the participants' confidence in their performance by validating their trajectories through the color-changing visual guide and providing visual reference points for anatomy that could otherwise be challenging to imagine as a new trainee for this procedure.

Comparison With Other Studies

Several prior studies have discussed the limitations of a traditional craniostomy procedure. Ravina et al. demonstrated the benefit of a conical drill bit in permitting a wider range of catheter trajectories.[22] Umana et al. described a novel device to ensure perpendicular craniostomy drilling and demonstrated the benefit to subsequent accuracy of catheter placement.[26] Prior studies demonstrating the benefit of mixed reality catheter guidance used predrilled craniostomies,[13,20,21] and/or static visualizations of the Kocher's point,[14–17] eliminating this critical portion of the procedure from their assessments. To the extent that EVD procedures in the future may use navigational assistance, for example, with mixed reality, our study suggests that

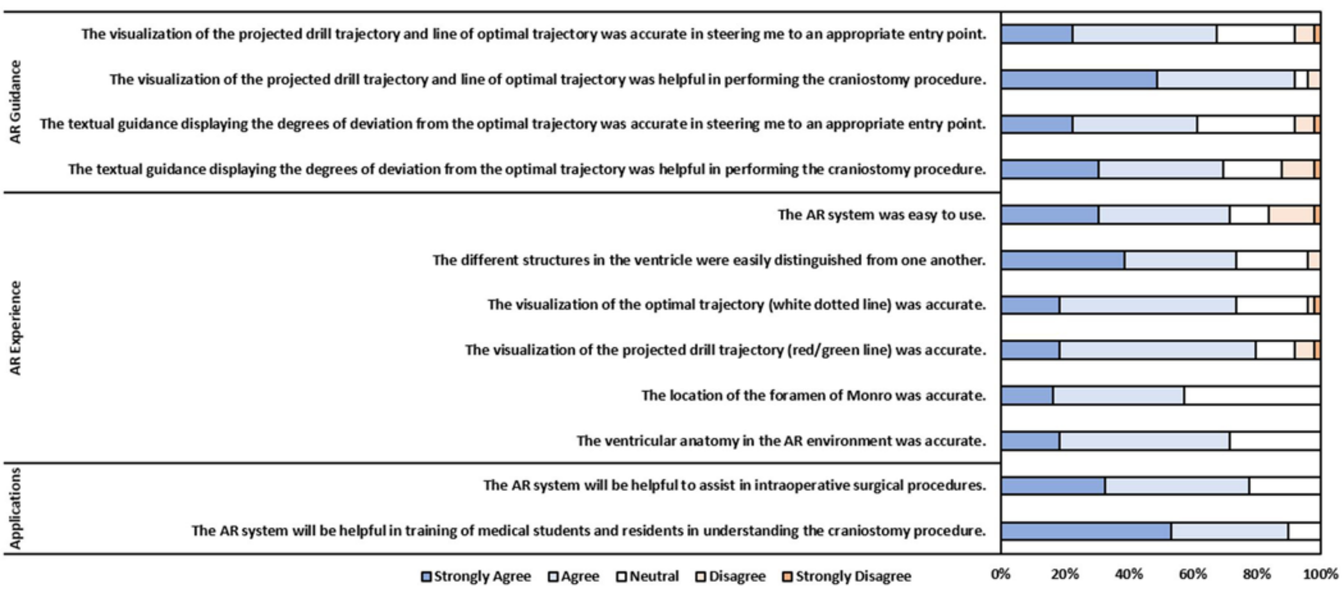

FIG. 6. Participant responses to structured postprocedure survey. Horizontal bar chart of the percentage of participants indicating the level of agreement or disagreement (Likert scale) with statements regarding mixed reality guidance during the procedure, the overall mixed reality experience, and relevance to education or clinical neurosurgery for 49 participants. AR = augmented reality.

real-time guidance of the craniostomy portion of the procedure is a critical step to the successful placement of the catheter and should be incorporated into the design of a navigated EVD procedure.

Strengths and Limitations

Historically, a CT scan has been required to determine the final position and accuracy of the catheter tip in EVD design studies. Our study reports the first known use of an image capture system to assess EVD placement. This system allowed for increased efficiency and reproducibility of the study and allowed us to perform a large number of user trials and achieve statistically compelling conclusions. Furthermore, we believe that our study benefited from a large number of naive users of uniform demographics simulating how this simulation may benefit the education of new trainees. Paired analysis of this group increased the statistical power. The lack of experience of this group, however, does limit the potential applicability of the results to more experienced users. While junior neurosurgical trainees have often not performed an EVD procedure prior to residency, they are likely more familiar with the anatomy, purpose, and steps of the procedure than our cohort.

Conclusions

Advances in assistive technologies permit safer and more accurate neurosurgical procedures. We have demonstrated in this study that a navigated twist-drill craniostomy using mixed reality guidance improves the accuracy of subsequent catheter placement compared with the traditional blind EVD procedure. While prior studies have shown the benefit of mixed reality guidance specifically for catheter placement, an accurately performed craniostomy further enables the subsequent step with the catheter. We suggest that future studies of EVD navigation incorporate this critical step to provide the highest degree of accuracy for the entire procedure leading to safely and successfully placed EVDs. Further research and optimization are needed to determine the feasibility of this technology in the patient setting.

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References

1. Shtaya A, Roach J, Sadek AR, Gaastra B, Hempenstall J, Bulters D. Image guidance and improved accuracy of external ventricular drain tip position particularly in patients with small ventricles. *J Neurosurg*. 2018;130(4):1268-1273.
2. Reisch R, Stadie A, Kockro RA, Hopf N. The keyhole concept in neurosurgery. *World Neurosurg*. 2013;79(2 Suppl):S17.e9-S17.e13.
3. Vaishnav AS, Othman YA, Virk SS, Gang CH, Qureshi SA. Current state of minimally invasive spine surgery. *J Spine Surg*. 2019;5(suppl 1):S2-S10.
4. Meola A, Cutolo F, Carbone M, Cagnazzo F, Ferrari M, Ferrari V. Augmented reality in neurosurgery: a systematic review. *Neurosurg Rev*. 2017;40(4):537-548.
5. Chen L, Day TW, Tang W, John NW. Recent developments and future challenges in medical mixed reality. In: *2017 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE; 2017:123-135. Accessed November 15, 2023. https://ieeexplore.ieee.org/document/8115411
6. Guha D, Alotaibi NM, Nguyen N, Gupta S, McFaul C, Yang VXD. Augmented reality in neurosurgery: a review of current concepts and emerging applications. *Can J Neurol Sci*. 2017;44(3):235-245.
7. Chidambaram S, Stifano V, Demetres M, et al. Applications of augmented reality in the neurosurgical operating room: a systematic review of the literature. *J Clin Neurosci*. 2021;91:43-61.
8. Fick T, van Doormaal JAM, Hoving EW, Regli L, van Doormaal TPC. Holographic patient tracking after bed movement for augmented reality neuronavigation using a head-mounted display. *Acta Neurochir (Wien)*. 2021;163(4):879-884.
9. Qi Z, Li Y, Xu X, et al. Holographic mixed-reality neuronavigation with a head-mounted device: technical feasibility and clinical application. *Neurosurg Focus*. 2021;51(2):E22.
10. Kunz C, Hlavac M, Schneider M, et al. Autonomous planning and intraoperative augmented reality navigation for neurosurgery. *IEEE T Med Robot Bio*. 2021;3(3):738-749.
11. Haemmerli J, Davidovic A, Meling TR, Chavaz L, Schaller K, Bijlenga P. Evaluation of the precision of operative augmented reality compared to standard neuronavigation using a 3D-printed skull. *Neurosurg Focus*. 2021;50(1):E17.
12. Yavas G, Caliskan KE, Cagli MS. Three-dimensional-printed marker-based augmented reality neuronavigation: a new neuronavigation technique. *Neurosurg Focus*. 2021;51(2):E20.
13. Gibby W, Cvetko S, Gibby A, et al. The application of augmented reality–based navigation for accurate target acquisition of deep brain sites: advances in neurosurgical guidance. *J Neurosurg*. 2021;137(2):489-495.
14. Li Y, Chen X, Wang N, et al. A wearable mixed-reality holographic computer for guiding external ventricular drain insertion at the bedside. *J Neurosurg*. 2018;131(5):1599-1606.
15. Van Gestel F, Frantz T, Vannerom C, et al. The effect of augmented reality on the accuracy and learning curve of external ventricular drain placement. *Neurosurg Focus*. 2021;51(2):E8.
16. Schneider M, Kunz C, Pal’a A, Wirtz CR, Mathis-Ullrich F, Hlaváč M. Augmented reality-assisted ventriculostomy. *Neurosurg Focus*. 2021;50(1):E16.
17. Skyrman S, Lai M, Edström E, et al. Augmented reality navigation for cranial biopsy and external ventricular drain insertion. *Neurosurg Focus*. 2021;51(2):E7.
18. Greenberg MS. *Handbook of Neurosurgery*. 7th ed. Greenberg Graphics; 2010:xiv.
19. Ofoma H, Cheaney B II, Brown NJ, et al. Updates on techniques and technology to optimize external ventricular drain placement: a review of the literature. *Clin Neurol Neurosurg*. 2022;213:107126.
20. Eom S, Sykes D, Rahimpour S, Gorlatova M. NeuroLens: augmented reality-based contextual guidance through surgical tool tracking in neurosurgery. In: *2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE; 2022:355-364. Accessed November 15, 2023. https://ieeexplore.ieee.org/abstract/document/9995485
21. Eom S, Kim S, Rahimpour S, Gorlatova M. AR-assisted surgical guidance system for ventriculostomy. In: *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE; 2022:393-396. Accessed November 15, 2023. https://ieeexplore.ieee.org/document/9757461
22. Ravina K, Yang N, Brocoum S, et al. Conical drill bit for optimized external ventricular drain placement: a proof-of-concept study. *J Neurosurg*. 2023;139(3):881-891.

23. Fedorov A, Beichel R, Kalpathy-Cramer J, et al. 3D Slicer as an image computing platform for the Quantitative Imaging Network. *Magn Reson Imaging*. 2012;30(9):1323-1341.
24. Mackle EC, Shapey J, Maneas E, et al. Patient-specific polyvinyl alcohol phantom fabrication with ultrasound and x-ray contrast for brain tumor surgery planning. *J Vis Exp*. 2020;(161):10.3791/61344.
25. Podkovik S, Patchana T, Farr S, et al. External ventricular drain (EVD) placement using a hands-on training session on a simple three-dimensional (3D) model. *Cureus*. 2022;14(8):e28014.
26. Umana GE, Scalia G, Yagmurlu K, et al. Multimodal simulation of a novel device for a safe and effective external ventricular drain placement. *Front Neurosci*. 2021;15:690705.

Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Jackson, Eom, Ma, Hu, Sykes, Gorlatova. Acquisition of data: Eom, Ma, Vutakuri, Hu. Analysis and interpretation of data: Jackson, Eom, Ma, Hu, Haskell-Mendoza. Drafting the article: all authors. Critically revising the article: Jackson, Eom, Ma, Hu, Haskell-Mendoza, Sykes, Gorlatova. Reviewed submitted version of manuscript: Jackson, Eom, Vutakuri, Hu, Haskell-Mendoza, Sykes, Gorlatova. Approved the final version of the manuscript on behalf of all authors: Jackson. Statistical analysis: Jackson, Eom, Ma, Hu, Haskell-Mendoza. Administrative/technical/material support: Ma, Haskell-Mendoza. Study supervision: Jackson, Gorlatova.

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