

Augmented reality–assisted ventriculostomy

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OBJECTIVE Placement of a ventricular drain is one of the most common neurosurgical procedures. However, a higher rate of successful placements with this freehand procedure is desirable. The authors' objective was to develop a compact navigational augmented reality (AR)–based tool that does not require rigid patient head fixation, to support the surgeon during the operation.

METHODS Segmentation and tracking algorithms were developed. A commercially available Microsoft HoloLens AR headset in conjunction with Vuforia marker-based tracking was used to provide guidance for ventriculostomy in a custom-made 3D-printed head model. Eleven surgeons conducted a series of tests to place a total of 110 external ventricular drains under holographic guidance. The HoloLens was the sole active component; no rigid head fixation was necessary. CT was used to obtain puncture results and quantify success rates as well as precision of the suggested setup.

RESULTS In the proposed setup, the system worked reliably and performed well. The reported application showed an overall ventriculostomy success rate of 68.2%. The offset from the reference trajectory as displayed in the hologram was 5.2 ± 2.6 mm (mean \pm standard deviation). A subgroup conducted a second series of punctures in which results and precision improved significantly. For most participants it was their first encounter with AR headset technology and the overall feedback was positive.

CONCLUSIONS To the authors' knowledge, this is the first report on marker-based, AR-guided ventriculostomy. The results from this first application are encouraging. The authors would expect good acceptance of this compact navigation device in a supposed clinical implementation and assume a steep learning curve in the application of this technique. To achieve this translation, further development of the marker system and implementation of the new hardware generation are planned. Further testing to address visuospatial issues is needed prior to application in humans.

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KEYWORDS ventriculostomy; ventricular puncture; ventricular drain; augmented reality; Holomed; HoloLens

THE ventriculostomy is among the most common operations in neurosurgical practice, either as a standalone procedure, such as in placement of an external ventricular drain (EVD), or as part of a more complex operation, such as the implantation of a shunt system.¹ The procedure is usually conducted freehand, using visible or palpable anatomical landmarks for orientation.² This remains true even in times of widespread availability of technical aids such as neuronavigation systems, whose setup and application are often considered too time-consuming.³ The underlying tradeoff can put patients at risk, because freehand ventriculostomy results in an optimal position of the catheter in only 60% of cases.⁴ Therefore, the search for a safer and more precise way to perform ventriculostomy is ongoing.

Augmented reality (AR) is widely known in the field of neurosurgery, mainly in terms of superimposed neuro-

navigational data inside operating microscopes.⁵ Technical advances in recent years allowed the development of head-mounted, mobile AR devices, such as the Microsoft HoloLens, available since 2015. The holographic functionality in this device is self-contained.⁶ It enables the wearer to visualize 3D imaging and anatomical data that can be superimposed onto a patient.⁷ As with any navigation system, the setup is susceptible to movements, and tracking can be challenging. However, significant improvement of negative effects such as spatial instability and hologram drift can be achieved by the use of marker tracking.⁸

The aim of this project was to develop a tool that provides the surgeon with AR guidance during a ventriculostomy to improve the precision and safety of the procedure. Commercially available Microsoft HoloLens AR glasses are the sole active component in the described setup. Entry point and target area are visualized as a 3D

ABBREVIATIONS AR = augmented reality; EVD = external ventricular drain.

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hologram on the surface of a head model. To improve the acceptance of the system, minimal delay or disruption in the workflow of this standard procedure was mandatory. As part of the project, various items were developed: 1) a fast-performing, automatic segmentation algorithm for the cranial anatomy (< 6 seconds), derived from a CT scan; 2) a marker system capable of holding a variety of markers (ArUco, Vuforia, infrared), designed to cover the process change from nonsterile to sterile with very high repeatability of less than 0.15 mm (during the experiments, Vuforia markers were used); and 3) a custom-made, 3D-printed, phantom head model for testing the system with 5 different exchangeable ventricular systems, inspired by real patient anatomy. With these prerequisites achieved, a series of test punctures on phantom heads were conducted by neurosurgeons and neurosurgical trainees of different levels of experience.

Methods

The study was approved by the local ethics committee of the University of Ulm and therefore performed in accordance with the ethical standards outlined in the Declaration of Helsinki. One hundred routine cranial CT scans of patients with or without abnormal findings were exported from the hospital's imaging archive. The scans were used to develop and train an automatic segmentation algorithm that allowed the creation of a 3D model of the skin surface, bone, and lateral ventricles; details have been described elsewhere.⁹ The algorithm was later used to create the holograms displayed to the surgeons in the test series.

Head Models

In total, two different head models were used in this study. A proof of concept was performed on a commercially available Synbone phantom head with silicone skin, a foam brain, and a (relatively large) air-filled ventricular system. This validated the setup initially before a series of test punctures was conducted.

To test how the system and surgeon would perform, the intention was to have challenging cases with anatomical variation of the ventricles throughout the test series. Therefore, significantly deformed ventricles due to a space-occupying intracranial lesion, and differences in size and abnormalities such as a midline shift, were intentionally chosen. This led to the development of a custom-made head model, which was achieved through several iterations. The shape of the final version that was used for the test was composed of multiple CT scans. The skull was 3D-printed with acrylonitrile styrene acrylate filament (Stratasys) and harbored a base into which a ventricular system could be fixed. The convexity of the skull consisted of a "skull cap" that could be drilled and swapped without the need to replace the whole model after one test session.

Shapes for the 5 different ventricular systems were derived from CT scans. Three-dimensional-printed templates were created that could be equipped with modeling clay to repeat the same shape in every series. For preparation of the test punctures, they were placed into sockets

inside the head models. With the skulls made in a watertight fashion, they were then filled with agar gel that when cooled and hardened resembled brain tissue.¹⁰

Data sets of the above-mentioned holograms were imported into the HoloLens and stored in an application (app) rather than being reprocessed every time, to keep the workflow during the test punctures as streamlined as possible. In the operating room, the head model was equipped with the developed marker system holding a feature-based marker attached to the forehead. Commercially available markers from the Vuforia library (PTC Inc.) were used because good precision and tracking stability had been shown in the literature already.⁸

With the hologram loaded on the HoloLens and the navigation app running, automatic recognition of the marker allowed for approximate positioning and coarse registration of the hologram relative to the marker. However, automatic recognition of the head surface could not be achieved robustly with the present generation of the HoloLens' hardware. As a workaround for fine registration, this step had to be performed using a gaming controller to have the hologram and head aligned. This approach was chosen in the initial feasibility tests, where it worked reliably. In the test series, all head surfaces were identical and the marker was always attached in the same position. With the spatial information saved in the app, the HoloLens recognized the marker and correctly displayed the hologram onto the head, making the controller-based registration process redundant. Sterile drapes were used in a feasibility setup but not in the test series. One filling of agar with the respective ventricular system was used for three consecutive test series before it had to be replaced.

Testers and Procedures

A total of 6 neurosurgeons and 5 neurosurgical residents took part in the study. Before the test series, every participant was shown a teaching video. The app and the planned procedure were explained. The individual pupillary distance of each tester was recorded in the HoloLens settings. For reference purposes, during the punctures a hologram of the marker system was projected over the real marker. This allowed the wearer to verify the accuracy of the registration during the procedure. Correct alignment of the hologram with the head model as well as the marker could be verified by the surgeon at any time. With the gaming controller, several layers such as skin, skull, ventricular system, Kocher's point, puncture trajectory, and combinations could be toggled freely.

The procedure started with two burr hole trepanations in the skull cap at the displayed Kocher's points. A standard surgical drill (Stryker Corp.) was used. Most participants then switched to a display of the ventricular system and trajectories alone to minimize distractions. A standard ventricular catheter on a stylet was then navigated through the burr hole and agar into the ventricular system. Only one puncture was allowed in the test setting, so corrections for new trajectories were ruled out. After placing two drains, the skull cap was moved to the second head while the respective data set was loaded into the app. The surgeons did not know the different ventricular system shapes in each head beforehand, so they



FIG. 1. A: Drilling a burr hole. B: Aiming for the ipsilateral frontal horn. C: Advancing the catheter under AR guidance.

were allowed to familiarize themselves, walking around the head and having a “3D look.” After another two drain insertions, the cap was moved to the next head, and so on. This way, each participant drilled two holes and placed a total of 10 EVDs in 5 heads. The heads were then taken for a CT scan and evaluation (Siemens Healthcare; Figs. 1–3).

Outcomes and Evaluation

A successful ventriculostomy (“hit”) was considered the main target of the test series. Whenever there was an offset from the reference entry point into the frontal horn as displayed in the hologram, the euclidean distance was measured to quantify precision. If an attempt was unsuccessful (“miss”), the deviation of the actual puncture to the reference trajectory as displayed in the hologram was calculated. To do so, the length of the vector from reference Kocher’s point to reference target point was applied to the actual trepanation point, following the vector of the inserted EVD. The distance between the endpoint (with reference length) of the inserted EVD and the target point was considered the error (Fig. 4).

For analysis purposes, a reference CT scan of the head model was obtained, which carried markers for entry and target point in accordance with the displayed hologram. Participants 1–3 performed a second series of test punctures under the same conditions in anticipation of a learning curve. After the test series, all participants filled out a form to rate the following items on a Likert scale, from 5 (strongly agree) to 1 (strongly disagree), and were asked to comment on the system; the items were: 1) the system is convenient to use; 2) I already have experience with head-mounted virtual reality/AR devices; and 3) I already have experience with this system (person was involved in project development).

Results

All participants finished a complete test series and no incomplete data sets had to be considered in the analysis. No exclusion from the study had to be made. Surgeon experience ranged from 3.5 to 30 years (mean 13.4 ± 8.9 years). In summary, 22 burr holes were drilled in 11 skull caps, and 110 EVDs were placed, leading to 55 CT head scans. Seven participants wore glasses, and 3 of them wore

their glasses during the series. Double vision of some of the holograms was experienced by 2 participants. Almost all participants ($n = 10$) were right-handed.

Performance of the marker tracking averaged approximately 25 frames per second, enabling stable visualization. The overall system accuracy comprises several factors: the registration accuracy, the Vuforia tracking accuracy, and the hologram drift. To determine the registration error, a digital caliper was used to determine the hologram registration error ($n = 10$ for every axis) on phantom-integrated reference points, resulting in a mean error of 1.36 ± 1.33 mm for the x-axis, 1.45 ± 0.87 mm for the y-axis, and 1.19 ± 0.83 mm for the z-axis. The overall error for the 3 axes was 2.71 ± 1.18 mm. The Vuforia tracking ac-

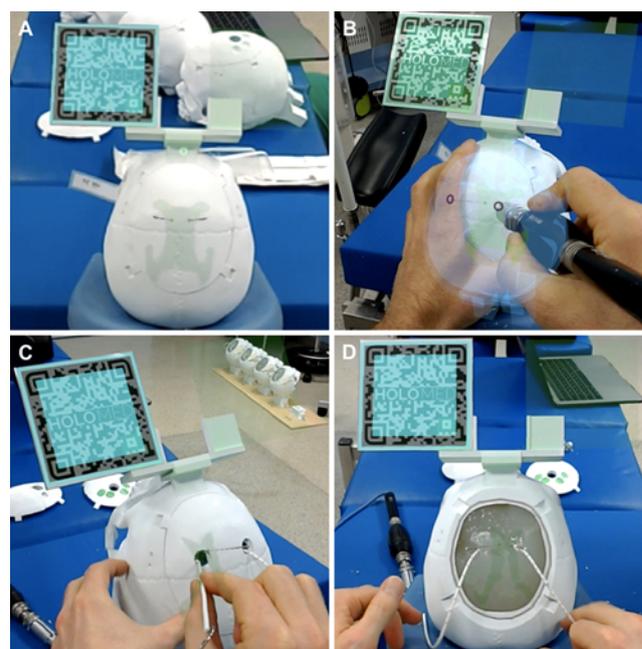


FIG. 2. Surgeon’s perspective/holographic view. A: Start of the procedure. B: Drilling, and holographic display of the skull, Kocher’s points, trajectory, and ventricular system. C: One drain inserted, placement of the second drain along the reference trajectory. The background shows head models ready for CT scans. D: Skull cap removed, agar filling visible, hologram of the ventricular system.

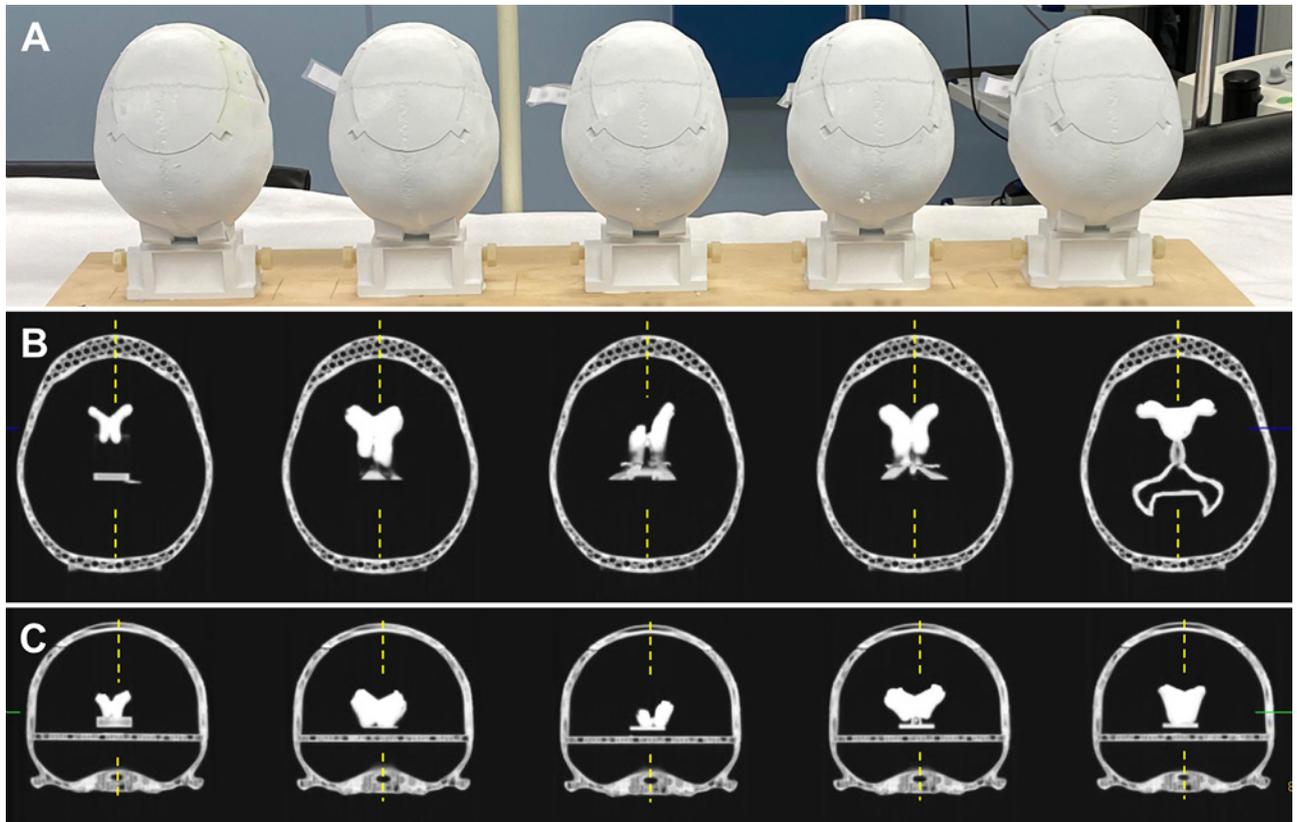


FIG. 3. A: Head models lined up as for CT. Note the intact/unused “skull caps.” **B and C:** Corresponding axial and coronal CT scans. The *dashed line* indicates the midline.

curacy was evaluated as 0.31 ± 0.38 mm,¹¹ and a mean drift of 1.41 ± 1.08 mm was determined by Frantz et al.⁸ The Vuforia tracking accuracy and the drift are most likely correlated. The complete system accuracy can be calculated as a sum of the error values using the formula: $e_{sys} = e_{reg} + e_{track} + e_{drift}$. This led to an overall optical error (e_{sys}) of 3.06 ± 2.47 mm.

The accuracy was identical in the feasibility setup, in which the marker head was swapped for application of sterile drapes.¹² The repeatability tested with a measuring arm (FARO) showed an accuracy of 0.19 ± 0.02 mm. If there was movement of the model, such as during drilling of the burr holes, the hologram reliably moved into the new position so manual correction was never necessary.

The following results involve the puncture series of all 11 participants (first attempt); second attempts of participants 1–3 are considered separately (see below). The overall hit rate was 68.2% (Fig. 5). The mean “error when hit” (d), as distance measured between the EVD entering the ventricle to the reference entry point as shown in the hologram, was 5.2 ± 2.6 mm (Fig. 4). The overall rate of misses was 31.8% (Fig. 5). Within this proportion, the mean deviation from the target (“error when missed,” e) was 10.9 ± 4.3 mm, according to the calculation described above (Fig. 4). The mean deviation from the reference trajectory calculated through all hit and missed punctures was 7.1 ± 4.1 mm.

Participants 1–3 took part in the test series and performed a second attempt later. Considered separately, they

performed worse than average in their first attempt, when the hit rate was 63.33%; the mean “error when hit” was 4.3 ± 1.7 mm. In their second attempt, participants 1–3 improved significantly to a hit rate of 93.3% and mean “error when hit” of 3.9 ± 2.0 mm.

Feedback

In general, participants found the system convenient to use (median Likert scale score of 4). Experience with head-mounted AR devices was limited (median Likert scale score of 3). The majority of participants were not involved in the project development (median Likert scale score of 2).

Discussion

Due to the high frequency of ventriculostomy in neurosurgical practice, complications resulting from failed puncture or inadequate anatomical position are relatively common.¹³ To improve precision, technical tools such as neuronavigation can be employed.¹⁴ Despite strong evidence that freehand ventriculostomy has been identified as a risk factor for malposition of ventricular catheters,¹⁵ a survey showed that neurosurgeons would be reluctant to use technical help if the time expense exceeded 10 minutes.³

Based on that issue, we aimed to develop an approach for AR-assisted ventriculostomy in which the AR glasses were the only additional active component of the setup.

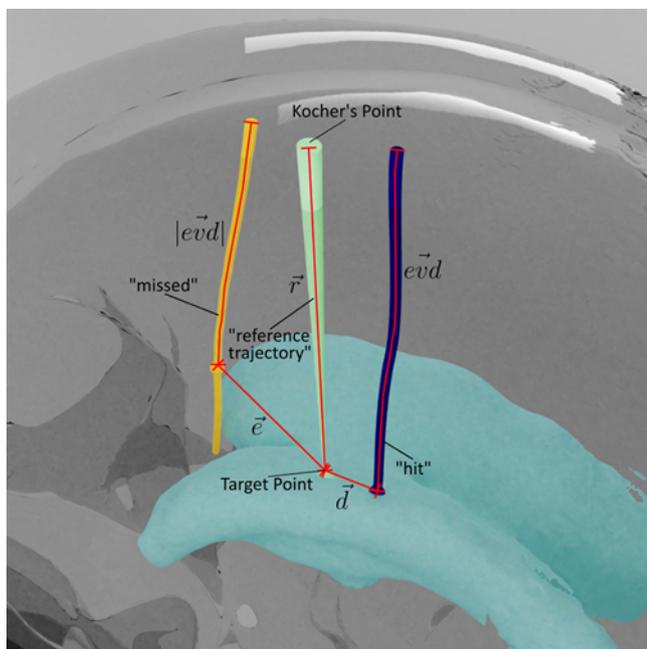


FIG. 4. Calculation metric. Three-dimensional reconstruction of a CT scan after puncture. Reference vector r connecting Kocher's and target points on the ventricular surface, as displayed in the hologram. Vector evd (external ventricular drain) in a successful attempt, distance d to quantify distance when hit. Vector $|evd|$ in an unsuccessful attempt, distance e to quantify error.

The aim was to create a compact navigation tool that was readily available and quick to use without the necessity of rigid head fixation of the patient. With a custom-made head model, segmentation software, and marker-based tracking, we conducted a series of AR-assisted ventriculostomies in an experimental setting.

To our knowledge, this is the first published work on marker-tracking, navigation-based, AR-guided ventriculostomy. Our first findings are positive from a technical as well as a clinical point of view. The setup worked reliably in a head model, which in our opinion is the first important step

in the transition toward clinical application. A limited number of surgeons who participated in the puncture series were familiar with AR headsets. For some surgeons it was their first encounter with this technology. However, the overall experience was rated positively and convenient to use.

Several limitations apply, however, when comparing the findings of the experimental setting with ventriculostomy in real patients, with regard to precision of the punctures; our results reflect the hit rate of freehand ventriculostomy described in the literature.^{2,4,16,17}

Participants 1–3 performed a second attempt in the puncture series, in which the average hit rate and precision improved significantly. This is a promising finding, because a steep learning curve may be assumed. However, future studies with an increased number of participants and repeated punctures will be necessary to address this hypothesis. In a patient ventriculostomy application we would expect a higher success rate due to effects such as the “loss of resistance” in a hit (see below). Using a different setup, Li et al. showed a significant improvement in precision when comparing AR-guided to freehand ventriculostomy in a small series of patients.¹⁸

Because tracking was based on a marker directly attached to the head, rigid head fixation as used by van Doormaal et al. (for example) was redundant.⁷ Time-consuming interruptions of the workflow, such as manual repositioning and reregistration of the hologram as described elsewhere, were not necessary.¹⁸ It has to be mentioned that the test setup used in the puncture series employed a preregistered hologram. If the present setup was to be used on a real patient, manual registration would be necessary as a first step (as addressed in the proof of concept), because resolution of the present-generation HoloLens' sensors do not allow for automatic recognition of facial or other anatomical details.

In this first step, our emphasis was on proof of concept and demonstrating feasibility. The HoloLens is not a medical device per se, and legal approval of the setup as a medical device was not yet part of the project at this stage, and thus only first steps were taken. Therefore, punctures were all conducted on head models. It is note-

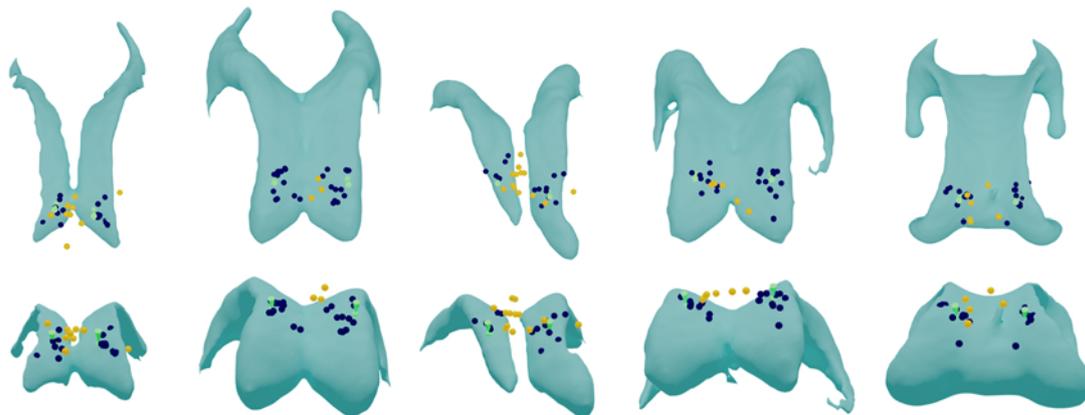


FIG. 5. Three-dimensional reconstruction of all 5 ventricular systems involved. The upper row is the top-down view; the lower row is the frontal view. Blue dots indicate a hit, yellow dots indicate a miss, and green cone represents a reference point displayed in the hologram. Note that due to the metric mentioned in the Methods, virtual “miss” points can float above the ventricular surface.

worthy that there are AR-based medical applications for the Microsoft HoloLens that already have received US FDA clearance (<https://www.novarad.net/post/novarad-s-opensight-augmented-reality-system-is-the-first-solution-for-microsoft-hololens-510-k-cle>).

The Synbone phantom head, used for the first proof of concept, comes with several advantages, such as a precisely manufactured skull and silicone skin. The haptic feedback, however, when advancing an EVD through foam into an air-filled ventricular system is different than the real procedure. This was one of the reasons why a custom-made model has been developed and manufactured as a 3D print for the test series. The consistency of the agar filling could be adjusted to resemble brain tissue to a satisfactory level. The characteristic “loss of resistance” in a hit, however, could not be achieved with the modeling clay used for the ventricular system, which rather led to an “increase of resistance” feedback. Also, there was no drainage of CSF in a successful puncture. When in a real patient the surgeon might have attempted a different trajectory, the experimental setting did not allow for a second try.

Another reason to use custom-made models was the economic consideration. A total of 11 participants each performing 5 punctures would have required a total of 55 heads, going beyond the financial scope of this project.

For practicality reasons, one filling of agar and ventricles was used for 3 puncture series, before they had to be replaced. Puncture entries remained visible in the agar's surface, even though the tracks inside the agar collapsed. However, the surgeon did not know if the predecessor's trajectory was successful.

The test series could show the feasibility of this approach as well as fast performance and good precision of the tracking. With an offset in the millimeter range, we yielded comparable results to those in the previously published literature.⁸

As part of the project, other marker libraries such as ArUco were tested,¹⁹ but the experience eventually favored Vuforia. For a future perspective, the use of infrared marker spheres is currently under investigation. Because there were promising findings even without an external light source, a change toward such markers that are already in frequent use in neuronavigation is planned.²⁰ Furthermore, with the HoloLens 2 ready for shipment, the next generation of hardware is nearly available and technical advances can be expected.

The developed system was designed with the ventriculostomy in mind. There is, of course, a varied spectrum of other possible applications in the field of neurosurgery, whenever navigation and image guidance are favored; examples might include 3D visualization of complex vascular malformations, planning for tumor resection, conduction of navigated (needle) biopsies, or placement of a drain into an intracerebral hematoma²¹ or abscess. In general, all lesions that are more unpredictable in size, shape, and position than the ventricular system might be an attractive field of application for a compact navigation tool.

There are known perceptual limitations to head-mounted AR systems such as the HoloLens.²² Although not explicitly tested for in this study, an impact on a demanding

visuospatial task such as ventriculostomy has to be assumed and a negative effect on the hit rate might result.

Originally, the intended site of application for the HoloLens was a living room environment rather than the operating room with its extreme light conditions. Also, in our setup holograms were displayed in a field within the length of an arm around the surgeon. Accordingly, the hardware was used at its limit in terms of hologram brightness as well as focal distance. At present, the user of a head-mounted AR device such as the HoloLens inevitably becomes subject to various optical errors.²² This might improve with future hardware generations such as the HoloLens 2, which features eye tracking (<https://docs.microsoft.com/en-us/windows/mixed-reality/design/eye-tracking>).

Some participants raised concerns about slight dizziness and headaches linked to using the system. These are known side effects in relation to using stereoscopic systems and they are well described in the literature.²³ Also, ergonomic aspects such as discomfort of the head and nose caused by wearing an operating room mask together with the HoloLens were mentioned.

Conclusions

We report our experience from the first application of a compact AR-based navigation tool in a series of test punctures in a head model. The results are promising and encouraging for a next step, such as testing in cadavers. We expect this system to be well received in neurosurgical practice. During the development of the tool, ergonomic aspects were of high priority. The setup had a low interference with the standard surgical workflow and the additional time expenditure was low. The lack of a rigid head fixation, and the AR headset being the sole active component of the setup, keeps the system simple. However, there are a number of obstacles to overcome before implementation in the operating room is feasible. More research on visuospatial perception and related errors is required. And there is the need for legal approval as a medical device.

With regard to economic aspects, resulting costs for commercial availability can only be estimated at this stage. The hardware expenses on the HoloLens itself are relatively modest at US \$3500. Running costs for a (disposable) marker system are negligible. The cost of regulatory compliance and technical support probably outweigh the hardware investment by an order of magnitude.

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References

1. Rosenbaum BP, Vadera S, Kelly ML, et al. Ventriculostomy: frequency, length of stay and in-hospital mortality in the United States of America, 1988–2010. *J Clin Neurosci*. 2014; 21(4):623–632.
2. Hsieh C-T, Chen G-J, Ma H-I, et al. The misplacement of external ventricular drain by freehand method in emergent neurosurgery. *Acta Neurol Belg*. 2011;111(1):22–28.

3. O'Neill BR, Velez DA, Braxton EE et al. A survey of ventriculostomy and intracranial pressure monitor placement practices. *Surg Neurol*. 2008;70(3):268–273.
4. Foreman PM, Hendrix P, Griessenauer CJ, et al. External ventricular drain placement in the intensive care unit versus operating room: evaluation of complications and accuracy. *Clin Neurol Neurosurg*. 2015;128:94–100.
5. Meola A, Cutolo F, Carbone M, et al. Augmented reality in neurosurgery: a systematic review. *Neurosurg Rev*. 2017;40(4):537–548.
6. Karmonik C, Boone TB, Khavari R. Workflow for visualization of neuroimaging data with an augmented reality device. *J Digit Imaging*. 2018;31(1):26–31.
7. van Doormaal TPC, van Doormaal JAM, Mensink T. Clinical accuracy of holographic navigation using point-based registration on augmented-reality glasses. *Oper Neurosurg (Hagerstown)*. 2019;17(6):588–593.
8. Frantz T, Jansen B, Duerinck J, Vandemeulebroucke J. Augmenting Microsoft's HoloLens with Vuforia tracking for neuronavigation. *Health Technol Lett*. 2018;5(5):221–225.
9. Kunz C, Heinrich P, Scheikl PM, et al. Fast volumetric auto-segmentation of head CT images in emergency situations for ventricular punctures. Paper presented at: CURAC 2019; September 19–21, 2019; Reutlingen, Germany.
10. Chen Z-J, Gillies GT, Broaddus WC, et al. A realistic brain tissue phantom for intraparenchymal infusion studies. *J Neurosurg*. 2004;101(2):314–322.
11. Kiss G, Palmer CL, Torp H. Patient adapted augmented reality system for real-time echocardiographic applications. In: Linte C, Yaniv Z, Fallavollita P, eds. *Lecture Notes in Computer Science*. Vol 9365. Springer International Publishing; 2015:145–154.
12. Kunz C, Schneider M, Hlavac M, et al. Augmented reality-assisted ventricular puncture with marker-based scene registration. *Int J CARS*. 2019;14:151–152.
13. Mansoor N, Madsbu MA, Mansoor NM, et al. Accuracy and complication rates of external ventricular drain placement with twist drill and bolt system versus standard trephine and tunnelation: a retrospective population-based study. *Acta Neurochir (Wien)*. 2020;162(4):755–761.
14. AlAzri A, Mok K, Chankowsky J, et al. Placement accuracy of external ventricular drain when comparing freehand insertion to neuronavigation guidance in severe traumatic brain injury. *Acta Neurochir (Wien)*. 2017;159(8):1399–1411.
15. Wilson TJ, Stetler WR Jr, Al-Holou WN, Sullivan SE. Comparison of the accuracy of ventricular catheter placement using freehand placement, ultrasonic guidance, and stereotactic neuronavigation. *J Neurosurg*. 2013;119(1):66–70.
16. Kakarla UK, Kim LJ, Chang SW et al. Safety and accuracy of bedside external ventricular drain placement. *Neurosurgery*. 2008;63(1 Suppl 1):ONS162-6–ONS166-7.
17. Huyette DR, Turnbow BJ, Kaufman C, et al. Accuracy of the freehand pass technique for ventriculostomy catheter placement: retrospective assessment using computed tomography scans. *J Neurosurg*. 2008;108(1):88–91.
18. 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.
19. Kunz C, Genten V, Meissner P, Hein B. Metric-based evaluation of fiducial markers for medical procedures. Paper presented at: Medical Imaging 2019: Image-Guided Procedures, Robotic Interventions, and Modeling; February 16–21, 2019; San Diego, CA.
20. Kunz C, Maurer P, Kees F, et al. Infrared marker tracking with the HoloLens for neurosurgical interventions. Paper presented at: CURAC 2020; September 17–19, 2020; Hamburg, Germany.
21. Awad IA, Polster SP, Carrión-Penagos J, et al. Surgical performance determines functional outcome benefit in the minimally invasive surgery plus recombinant tissue plasminogen activator for intracerebral hemorrhage evacuation (MISTIE) procedure. *Neurosurgery*. 2019;84(6):1157–1168.
22. Condino S, Carbone M, Piazza R, et al. Perceptual limits of optical see-through visors for augmented reality guidance of manual tasks. *IEEE Trans Biomed Eng*. 2020;67(2):411–419.
23. Hu X, Hua H. Design and assessment of a depth-fused multifocal-plane display prototype. *J Disp Technol*. 2014;10(4):308–316.

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: all authors. Acquisition of data: Schneider, Kunz, Pal'a, Hlaváč. Analysis and interpretation of data: Schneider, Kunz, Pal'a, Hlaváč. Drafting the article: Schneider, Kunz, Pal'a. Critically revising the article: Schneider, Kunz, Pal'a, Mathis-Ullrich, Hlaváč. Reviewed submitted version of manuscript: Kunz, Pal'a, Mathis-Ullrich, Hlaváč. Approved the final version of the manuscript on behalf of all authors: Schneider. Administrative/technical/material support: Wirtz, Mathis-Ullrich, Hlaváč. Study supervision: Wirtz.

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