Initial Experience with Using a Structured Light 3D Scanner and Image Registration to Plan Bedside Subdural Evacuating Port System Placement

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■ BACKGROUND: **Chronic subdural hematoma evacuation can be achieved in select patients through bedside placement of the Subdural Evacuation Port System (SEPS; Medtronic, Inc., Dublin, Ireland). This procedure involves drilling a burr hole at the thickest part of the hematoma. Identifying this location is often difficult, given the variable tilt of available imaging and distant anatomic landmarks. This paper evaluates the feasibility and accuracy of a bedside navigation system that relies on visible light-based 3-dimensional (3D) scanning and image registration to a pre-procedure computed tomography scan. The information provided by this system may increase accuracy of the burr hole location.**

■ METHODS: **In Part 1, the accuracy of this system was evaluated using a rigid 3D printed phantom head with implanted fiducials. In Part 2, the navigation system was tested on 3 patients who underwent SEPS placement.**

■ RESULTS: **The error in registration of this system was less than 2.5 mm when tested on a rigid 3D printed phantom head. Fiducials located in the posterior aspect of the head were difficult to reliably capture. For the 3 patients who underwent 5 SEPS placements, the distance between anticipated SEPS burr hole location based on registration and actual burr hole location was less than 1cm.**

■ CONCLUSIONS: **A bedside cranial navigation system based on 3D scanning and image registration has been introduced. Such a system may increase the success rate of bedside procedures, such as SEPS placement. However, technical challenges such as the ability to scan hair and practical challenges such as minimization of patient movement during scans must be overcome.**

INTRODUCTION

Evacuation of a chronic subdural hematoma (CSDH) is one of the oldest and most effective procedures in neurosurgery.[1] Although this procedure is most commonly performed in the operating room, bedside drainage without the use of general anesthesia has been utilized in select patients since the 1970s.[2] A more recent advance in bedside CSDH evacuation involves the Subdural Evacuation Port System (SEPS; Medtronic, Inc., Dublin, Ireland), which was introduced in the early 2000s.[3] This procedure involves drilling a burr hole, driving a hollow screw through that hole, and connecting the screw to a Jackson-Pratt style suction reservoir. Purported benefits of this system include the treatment of elderly and sick patients who would otherwise not tolerate general anesthesia,[4] decreased bleeding,[4] decreased total treatment cost,[5] and decreased hospital length of stay.[5]

The optimal location for burr hole and screw placement is the point of greatest thickness of the subdural collection.[3,4] Identifying this location on the patient's scalp based solely on the pre-procedure computed tomography (CT) scan and anatomical landmarks can be challenging, especially for junior neurosurgery residents who most frequently perform these procedures.[6] To improve the accuracy of this procedure at the authors' institution, a fiducial is often affixed to the patient's head at the proposed burr hole location. A pre-procedure CT

Key words
- 3D scanning
- 3D printing
- Chronic subdural hematoma
- Image registration
- SEPS

Abbreviations and Acronyms
3D: 3-dimensional
CSDH: Chronic subdural hematoma
CT: Computed tomography
SEPS: Subdural Evacuation Port System

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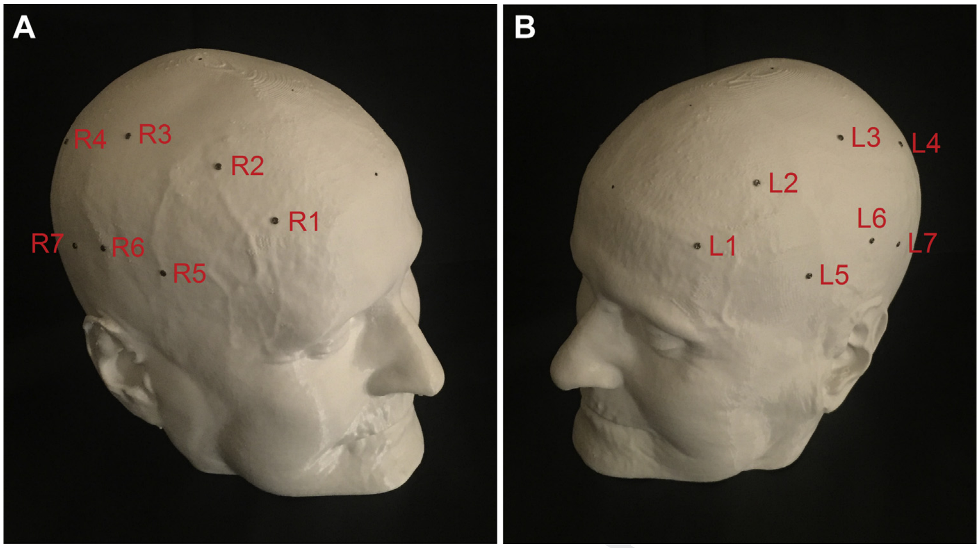

Figure 1. (**A**) Photograph of the right side (R) of the 3-dimensional printed phantom, with fiducial locations labeled in *red*. The fiducial was a titanium screw with a 3-mm head diameter. (**B**) Photograph of the left side (L) of the phantom.

scan is then obtained, and the location of the fiducial is compared with the location of maximal CSDH thickness. Adjustments are then made to the proposed burr hole location prior to the actual bedside surgical procedure. Although this method increases the accuracy of burr hole placement, it requires an additional CT scan and delays care.

This paper presents a preliminary evaluation of both the accuracy and clinical workflow of using a visible light-based 3-dimensional (3D) scanner and image registration to guide SEPS placement. The information that is generated from this system is similar to that of a CT scan with a fiducial placed at the proposed burr hole location. Benefits of this system compared with obtaining a second CT scan with fiducial placement may include decreased cost to the healthcare system, avoidance of radiation exposure, and expedited neurosurgical intervention.

METHODS

Testing of the navigation system consisted of two parts. The first part assessed the accuracy of registering a visible light-based 3D scan to a CT scan in an ideal, simulated setup. A 3D printed plastic head phantom with implanted fiducials was used to evaluate the error between marked locations on the 3D scan and the actual locations on a CT scan. The second part focused on the feasibility and accuracy of using the navigation system on 3 patients with CSDHs who underwent SEPS placement. The institutional review board approved this study under 45 CFR 46.110 (F)(1), (5), and (6), as the study posed minimal risk to participants.

Part 1: Accuracy Evaluation Using a Plastic Head Phantom with Implanted Fiducials

A 3D printed hollow plastic head was created using the methods described in a prior publication.[7] In brief, a CT scan of a "normal" person's head was obtained from an online DICOM image library (OsiriX, Pixmeo, Bernex, Switzerland). The 2-dimensional DICOM images were converted into 3D-printable format and printed on a 3D printer. Seven 3-mm diameter titanium screws were driven into each side of the head (Figures 1A and B). Four were implanted superior to the superior temporal line, with the remainder implanted in the temporal area. No screw was implanted in the midline or posterior fossa, as these are unlikely locations for a CSDH. A CT scan was obtained of the head at 0.8-mm slice thickness and reconstructed in 3D using Invesalius 3.0 (Invesalius, Information Technology Center Renato Archer, Amarais, Brazil) (Figure 2A).

Ten 3D scans using the visible light-based DAVID SLS-3 3D scanner (DAVID Vision Systems, Koblenz, Germany) were obtained of the right side of the head (Figure 2B). The scanner works by projecting various patterns of light through a standard multimedia projector. A camera at a fixed distance and angle with respect to the projector captures these patterns. An algorithm then generates a 3D surface based on the information that the camera provides. Each scan was taken from a different location at a distance of approximately 50 cm and at a location anterior, to the right of, and superior to the head. These locations captured the topologically rich facial features that are necessary for image registration. The different locations were intended to replicate realistic scenarios in which the location of the scanner relative to the patient's head is difficult to specify precisely. The same steps were repeated on the left side of the plastic head.

The results of the 3D scans were color surfaces in stereolithograph file format (Figure 2C). To register the 3D scan to the CT scan, coarse anatomical point correspondences (e.g., nose, lateral canthus, and tip of the ear) were manually selected.

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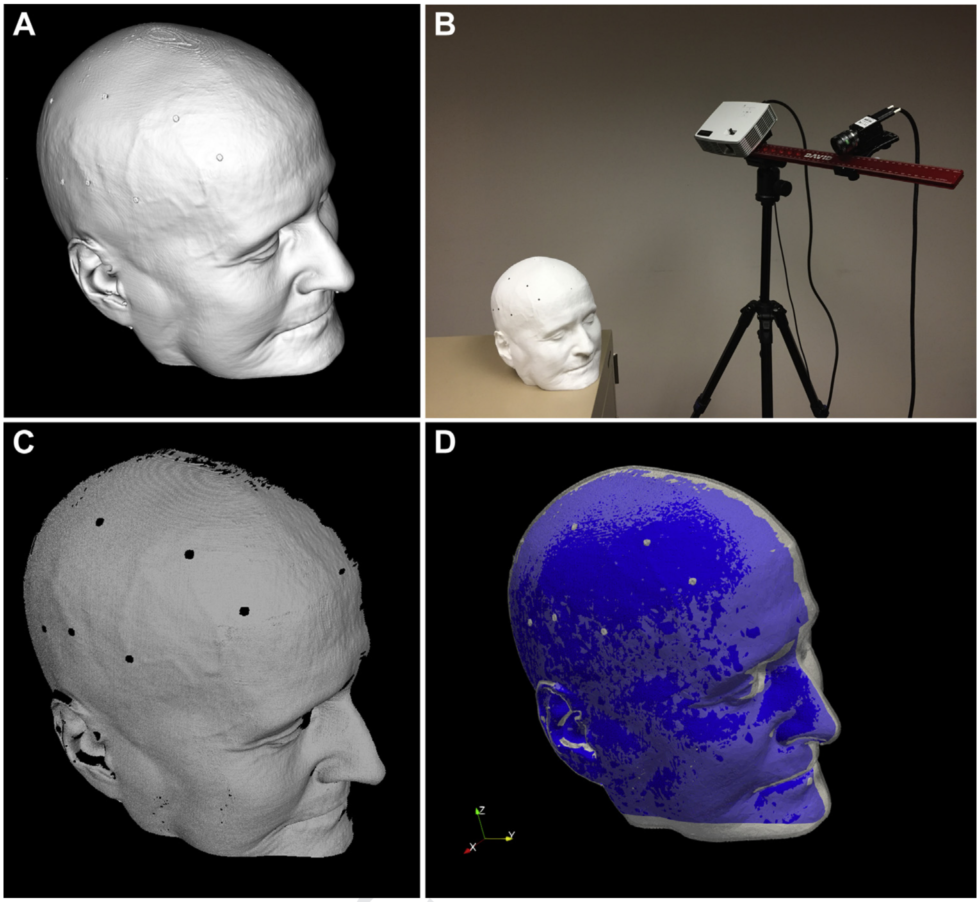

Figure 2. (**A**) Three-dimensional (3D) reconstruction of a computed tomography (CT) scan of the phantom. (**B**) The DAVID SLS-3 (DAVID Vision Systems, Koblenz, Germany) 3D scanner positioned to scan the phantom's left side. At the top of the tripod stand, the multimedia projector is on the left, and the high resolution video camera is on the right. Both are connected to a laptop (not displayed). (**C**) The 3D scan of the phantom's right side. The scan is in color. The screws appear as black holes in the scan due to their reflective properties. (**D**) Registration between the visible light-based 3D scan (*blue*) and the CT scan (*gray*). Areas in dark blue are areas where the 3D scan is closer to the observer, whereas areas in light blue are areas where the CT scan is closer to the observer.

Then a rigid registration using the method of Horn was performed.[8] Lastly, an iterative closest point surface registration was calculated for refinement (**Figure 2D**).[9] The registration process took approximately 1 minute.

Part 2: Feasibility and Accuracy of Using the Navigation System on Patients with CSDH

The system presented here aims to provide similar information to obtaining a CT scan with a fiducial placed at the proposed burr hole location. The *intended* workflow of the system involves shaving the patient's head at the location of the proposed burr hole. Then an "X" is made on the patient's scalp with a marking pen to enable identification by the visible light-based color 3D scanner as an initial working target. The 3D scan is then taken of the patient's head, with the "X" included in the scan (**Figure 3A**). The scanned surface is then registered to the patient's presenting CT scan with the CSDH, and axial, coronal, and sagittal cross sections corresponding to the center of the X are generated (**Figure 3B**). Based on this information, the location of the actual burr hole can be planned relative to the location of the marked "X".

To test the workflow and accuracy of this system, 3 CSDH patients were recruited. After consent was obtained, the general area close to the presumed location of the CSDH was shaved. An "X" mark was made with a surgical marker at the proposed location of skin incision and subsequent burr hole placement. At this time, a 3D scan of the patient's head was obtained. The scanning time was approximately 7 seconds. The SEPS placement then proceeded according to previously published protocols.[3] Specifically, the "X" mark made by the surgical marker specified the center of the actual skin incision and subsequent burr hole placement. Computational processing of the 3D scan and generation of the guidance

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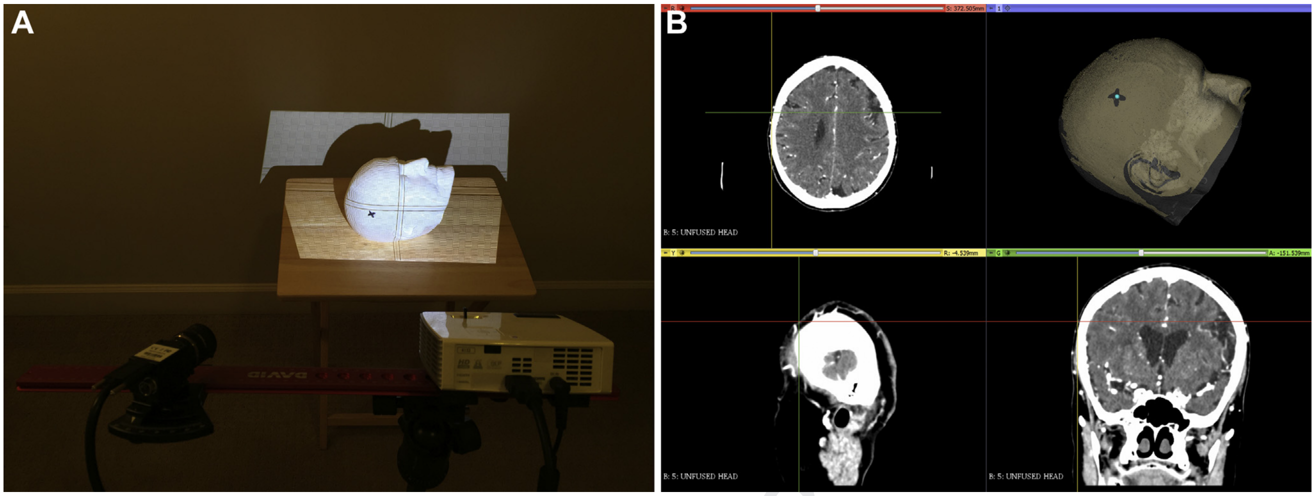

Figure 3. Demonstration of the workflow of the 3-dimensional (3D) navigation system. (**A**) The proposed location of the burr hole is marked as an "X" using a surgical marker. The patient's head is scanned by the visible light-based 3D scanner. (**B**) After aligning the 3D scan with the pre-procedure computed tomography (CT) scan, a navigation panel is presented, with coronal, sagittal, and axial views of the proposed burr hole location. The top right pane shows the alignment between the 3D scan and the CT scan. The panels are scrollable. The actual location where the burr hole will be drilled can be either the center of the "X" mark or adjusted based on the registration data presented in these panes.

panel occurred at a location separate from the procedure. Guidance information from the navigation system was not made available to the proceduralist due to the institutional review board requirement that navigation results not influence medical decision-making.

The distance between the anticipated burr hole location on the patient's skull and the actual location was used to evaluate the registration accuracy and utility of the guidance information. In essence, this is the error between where the proceduralist expects the burr hole to be based on navigation information and where it actually is after completion of the procedure. To calculate the anticipated burr hole location, the pre-procedure CT scan (**Figure 4A**) was registered to the 3D scan of the patient's scalp (**Figure 4B**) using the methods described in Part 1 (**Figure 4C**). The anticipated burr hole location was calculated as the closest point of the patient's skull to the center of the "X" mark on the patient's scalp, as described in prior publications.[10,11] The accuracy of this point was fundamentally dependent on the quality of registration between the 3D scan and the pre-procedure CT scan.

A post-SEPS removal CT scan was preferentially used to determine the actual location of the burr hole drilled into the skull. If one were not available, a CT with the SEPS drain in place was used. The actual burr hole location was defined as the center of the hole (or screw) on the surface of the skull in the post-procedure CT scan. The post-procedure skull was then registered to the pre-procedure skull using the methods described in Part 1. The error in registration between the skulls was less than 1 mm, as it is the registration between 2 rigid bones. Then the distance between the anticipated burr hole location (projected onto the pre-procedure skull) and the actual burr hole location (marked on the post-procedure skull) was calculated.

RESULTS

For Part 1 on the right side of the phantom, the mean error for each of the fiducials is listed in **Table 1**. Only 3 of the 10 scans were able to capture Point 4, which was located in the parietal-occipital area. Also, only 8 of the 10 scans were able to capture Point 7, which was located in the posterior temporal-occipital area. The mean error for each of the fiducials that was captured by all 10 scans was less than 2.0 mm.

The results for the left side of the phantom are also listed in **Table 1**. Only 6 of the 10 scans were able to capture Point 4. The mean errors for each of the fiducials that were captured by all 10 scans was less than 2.0 mm. For each of errors calculated for each of the fiducials, the largest error was 2.25 mm. **Table 1** lists the errors calculated for the 10 registrations on the right and left side of the phantom.

For Part 2, obtaining a 3D scan of the patient's shaved and marked head was more difficult than anticipated. Patients with CSDH frequently exhibited altered mental status and had difficulty holding their head still for even the 7 seconds needed to obtain the 3D scan. Initially, approximately 5 minutes were needed to obtain a successful scan. For later scans, an assistant held the patient's head during the scan. The assistant's hands were out of view of the 3D scanner. Information regarding the patients and their CSDHs is listed in **Table 2**. **Figure 4D** illustrates the navigation panel that can be generated after registration between the visible light-based 3D scan and the CT scan.

The distances between the anticipated burr hole location and the actual burr hole location are also listed in **Table 2**. Notably, the error in distance was less than 1 cm for all 5 SEPS drains placed.

DISCUSSION

Navigation systems for bedside procedures have not advanced as rapidly as those for procedures in the operating room. At the

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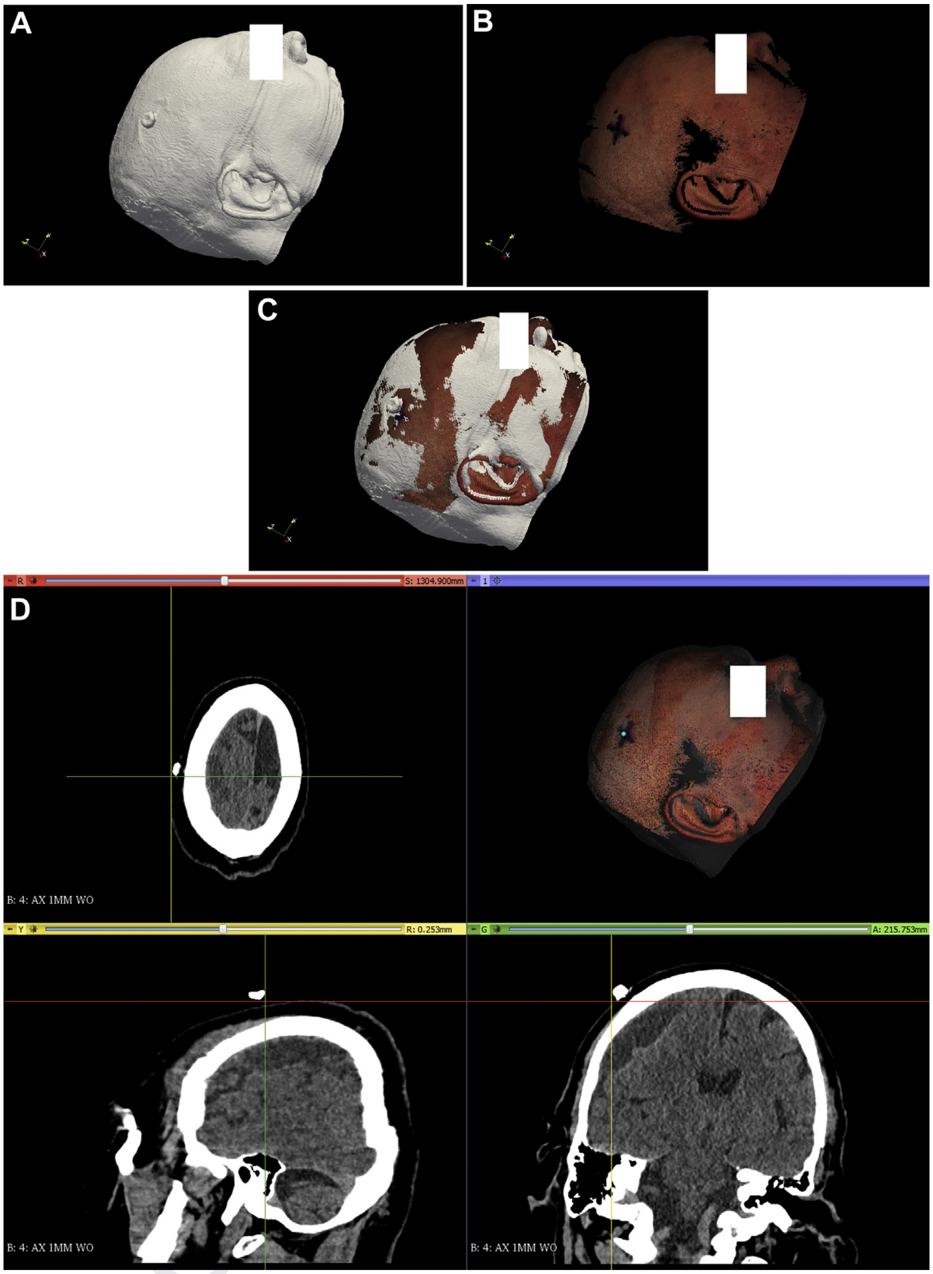

Figure 4. Evaluation of the 3-dimensional (3D) navigation system involving a patient with a chronic subdural hematoma who underwent Subdural Evacuation Port System (Medtronic, Inc., Dublin, Ireland) placement. (**A**) 3D reconstruction of the patient's head from a pre-procedure computed tomography (CT) scan. For this particular patient, a fiducial consisting of a metal hex nut was taped on the patient's head for the pre-procedure localizing CT scan. The initial CT scan obtained on patient presentation had too much movement and could not be used either for surgical procedure planning or for this project. The patient's eyes have been obscured for anonymity. (**B**) A color 3D scan of the patient's head with an "X" marking the proposed burr hole location. The proposed location is posterior and lateral to the hex nut's location, due to the recognition that the hex nut's location is too anterior and superior. Hair around the proposed burr hole area was generously shaved. Residual hair anterior and superior to the patient's ear appears as a void (*black*). (**C**) Registration between the CT scan and the visible light-based 3D scan of the patient. Beige areas are where the 3D scan surface is closer to the observer, and white areas are where the CT scan is closer to the observer. As expected, the "X" mark is posterior and lateral to the fiducial. (**D**) Navigation panel generated by the system. All views are aligned at the center of the "X" mark. The top left is the axial view of the patient's CT scan, top right is the alignment between the 3D scan and the CT scan, bottom left is the sagittal view, and bottom right is the coronal view. Cross-hairs indicate the center of the ink "X" mark on the 3D scan. All of the panels are scrollable.

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Table 1. Registration Error Between the Actual and Calculated Locations of the Fiducials Illustrated in **Figure 1**

	Avg Error	Std Dev	Max Error
R1	1.07	0.35	1.87
R2	1.21	0.23	1.76
R3	0.85	0.44	1.94
R4	-	-	-
R5	1.01	0.39	1.80
R6	1.02	0.30	1.61
R7	-	-	-
L1	1.20	0.47	1.71
L2	0.95	0.26	1.47
L3	1.10	0.22	1.52
L4	-	-	-
L5	1.28	0.57	2.25
L6	1.27	0.37	1.99
L7	1.57	0.45	2.22

Ten 3-dimensional (3D) surface scans were performed of the right side of the phantom. The 3D scans were registered to the computed tomography (CT) scan of the phantom. Distances between fiducial locations on the 3D surface scan and CT scan were calculated. The average, standard deviation, and maximum errors are presented. All measurements are in millimeters. If not all 10 scans captured the fiducial location, a "-" was entered in the table. All steps were repeated on the left side of the phantom. Avg Error, average error; Std Dev, standard deviation; Max Error, maximum error.

authors' institution, one method of increasing the accuracy of burr hole placement at the bedside involves obtaining a CT scan with a fiducial placed at the proposed burr hole site. Here, we evaluated the feasibility of using a visible light-based 3D scanner and image registration to guide SEPS drain placement for CSDHs. The navigation information provided by this system is made to resemble that of a CT scan with a fiducial located at the proposed burr hole site. Adjustments to the proposed incision site can be made by either measuring the change in distance using a ruler or repeating the registration process with a new "X" mark.

Part 1 involved a simplified test situation to evaluate the accuracy of the system presented here. The phantom's surface was rigid and uniform in color. The available errors in registration were all less than 2.5 mm and compare favorably with other methods of registration in neurosurgery.[12] The 3D scanner was unable to capture some of the posterior fiducials in several of the scans, which resulted in error values that were not available. Registration error in posterior locations is an inherent limitation of optical registration systems, which are reliant on the rich topographical anatomy of the face.[13]

In Part 2, the navigation system was tested in a clinical setting. The difficulty in having the CSDH patient hold their head still for 7 seconds was not anticipated. Multiple attempts at scans were made, eventually concluding with having an assistant hold the patient's head still while being out of view of the 3D scanner. The single 7-second scan initially took about 5–10 minutes to complete due to patient non-

Table 2. Information on the CSDHs of the 3 Patients

Patient	Location of CSDH	CSDH Size (cm)	Burr Hole Location	Error (mm)
1	Left Frontal, Parietal	13×7.5	Anterior	1.56
			Posterior	2.54
2	Right Frontal, Parietal	10×5.5	Anterior	3.31
			Posterior	9.55
3	Right Parietal	8.5×5.5	Center	6.03

The size of the chronic subdural hematoma (CSDH) was in centimeters and measured the anterior-posterior and superior-inferior lengths along the surface of the skull. **Figure 4** is based on Patient 3's data. Patients 1 and 2 had 2 Subdural Evacuation Port System (Medtronic, Inc., Dublin, Ireland) drains placed simultaneously due to the size of the CSDH. The errors in anticipated versus actual locations of the burr holes was calculated as described in the text.

cooperation. However at the end of our study, obtaining the scan took 1–2 minutes.

To evaluate the registration accuracy in a clinically relevant setting, we selected the distance between the anticipated burr hole location given by the "X" mark on the skin and the actual burr hole location. There were several sources of error in the calculated distance between the anticipated and actual burr hole locations on the skull. The first source was the alignment of the visible light-based 3D scan and the pre-procedure CT scan. This was the most important source of error that was evaluated. The second source was the calculation of the anticipated burr hole location based on the surface "X" mark. This calculation assumed that the drill bit for the burr hole was perpendicular to the skin surface, which was generally true. The third source of error was the alignment of the post-procedure skull CT with the pre-procedure skull CT, in which the coordinates of the anticipated burr hole were calculated. This alignment error is negligible, as it is an alignment between two rigid bones. The distances between the anticipated and the actual burr hole locations were 1.56, 2.54, 3.31, 9.55, and 6.03 mm (**Table 2**). All were less than 1 cm. The sizes of CSDHs requiring treatment were typically several centimeters in length and width. The errors that were reported would thus be acceptable for SEPS placement.

Prior studies have investigated the use of optical surface scanning to register patient-space information with image-space data. One of the first navigation devices to use optical surface registration involved a camera capturing the red dot of a laser pointer that is directed by the surgeon.[13,14] Laser range scanners could be used to automate the movements of the laser.[15,16] Most recently, commercially available visible light-based 3D scanners have been used to semi-automate the contact-based registration method that is commonly used.[17] Our study is the first to evaluate the use of a visible light-based 3D scanner to assist a bedside procedure in neurosurgery, the first clinical evaluation of 3D scanning for SEPS placement, and the first to use pen ink as a localizing fiducial.

Limitations of this study include the small number of patients, the inability to confirm registration during the procedure once the patient's face has been draped, and the absence of feedback from the proceduralist regarding the usefulness of the guidance information.

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In a more general sense, there are several challenges with using 3D scanning and image registration for neurosurgical planning. Two challenges include surfaces that are difficult to capture by 3D scanning and surfaces that are changed with respect to the pre-procedure CT scan.

Human hair is difficult for structured light 3D scanners to capture due to both the resolution of the scanner and hair's reflective properties.[18] Hair also cannot be used as a surface for registration due to it not appearing on the pre-procedure CT scan. In this study, a patch of hair was shaved around the proposed burr hole entry site. The skin surface at this area combined with facial features allowed the surface registration to be successful. At our institution, the shave for SEPS drain placement is generous, enabling visible light-based 3D scanning and registration to work. However, at other institutions, if the shave is minimal, visible light-based 3D scanning may not be successful.

Another challenge of using visible light-based 3D scanning involves surfaces that are obscured or deformed with respect to the pre-procedure CT scan. Examples include a Mayfield headholder, eyelid tape, or intubation tubing. In the study presented here, the patient was awake and not intubated. Facial features were then available for use as registration landmarks. The workflow demonstrated here may be difficult to generalize to other bedside procedures or surgeries in the operating room due to the reasons mentioned above.

CONCLUSIONS

In conclusion, this paper presents a navigation system using visible light-based 3D scanning and image registration for SEPS placement, a bedside procedure in neurosurgery. Knowledge of anatomical landmarks and the ability to match positions on a CT scan to locations on a patient are essential for every junior neurosurgery resident. When navigation systems based on 3D scanning and image registration are more mature, these systems may aid the junior resident to more accurately perform bedside procedures, including SEPS placement. Benefits of such navigation systems may include decreasing costs attributed to misplacement or CT scans guiding optimal placement.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Hansen Bow: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft. **Xiaochen Yang:** Conceptualization, Methodology, Software, Formal analysis. **Silky Chotai:** Investigation, Writing - review & editing. **Michael Feldman:** Investigation, Writing - review & editing. **Hong Yu:** Investigation, Supervision. **Dario Englot:** Conceptualization, Supervision. **Michael Miga:** Software, Resources, Supervision, Funding acquisition. **Benoit Dawant:** Software, Resources, Supervision, Funding acquisition. **Scott L. Parker:** Conceptualization, Methodology, Supervision, Project administration.

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