Frameless neuronavigation with computer vision and real-time tracking for bedside external ventricular drain placement: a cadaveric study

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OBJECTIVE A major obstacle to improving bedside neurosurgical procedure safety and accuracy with image guidance technologies is the lack of a rapidly deployable, real-time registration and tracking system for a moving patient. This deficiency explains the persistence of freehand placement of external ventricular drains, which has an inherent risk of inaccurate positioning, multiple passes, tract hemorrhage, and injury to adjacent brain parenchyma. Here, the authors introduce and validate a novel image registration and real-time tracking system for frameless stereotactic neuronavigation and catheter placement in the nonimmobilized patient.

METHODS Computer vision technology was used to develop an algorithm that performed near-continuous, automatic, and marker-less image registration. The program fuses a subject’s preprocedure CT scans to live 3D camera images (Snap-Surface), and patient movement is incorporated by artificial intelligence–driven recalibration (Real-Track). The surface registration error (SRE) and target registration error (TRE) were calculated for 5 cadaveric heads that underwent serial movements (fast and slow velocity roll, pitch, and yaw motions) and several test conditions, such as surgical draping with limited anatomical exposure and differential subject lighting. Six catheters were placed in each cadaveric head (30 total placements) with a simulated sterile technique. Postprocedure CT scans allowed comparison of planned and actual catheter positions for user error calculation.

RESULTS Registration was successful for all 5 cadaveric specimens, with an overall mean (± standard deviation) SRE of 0.429 ± 0.108 mm for the catheter placements. Accuracy of TRE was maintained under 1.2 mm throughout specimen movements of low and high velocities of roll, pitch, and yaw, with the slowest recalibration time of 0.23 seconds. There were no statistically significant differences in SRE when the specimens were draped or fully undraped (p = 0.336). Performing registration in a bright versus a dimly lit environment had no statistically significant effect on SRE (p = 0.742 and 0.859, respectively). For the catheter placements, mean TRE was 0.862 ± 0.322 mm and mean user error (difference between target and actual catheter tip) was 1.674 ± 1.195 mm.

CONCLUSIONS This computer vision–based registration system provided real-time tracking of cadaveric heads with a recalibration time of less than one-quarter of a second with submillimetric accuracy and enabled catheter placements with millimetric accuracy. Using this approach to guide bedside ventriculostomy could reduce complications, improve safety, and be extrapolated to other frameless stereotactic applications in awake, nonimmobilized patients.

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The execution of accurate, precise, and efficient procedures in mobile subjects remains a challenge in many surgical fields, including neurosurgery, in which ventriculostomy, for example, is among the most frequently performed neurosurgical interventions. This procedure is often performed on awake, nonimmobilized patients. As early as the intern year, trainees learn to perform this often emergency procedure at the patient’s bedside for the acute treatment of hydrocephalus and/or intracranial pressure monitoring. Despite technological advancements to facilitate catheter placement, the majority of these external ventricular drains (EVDs) are placed freehand using anatomical landmarks and require operators to cognitively correct in real time for patient-specific abnormalities such as intracranial shift and patient movement.

This freehand method has remained the unaltered standard of care since the inception of ventriculostomy procedures by Claude-Nicholas Le Cat in 1844 and the description of Kocher’s point in 1894. As we strive to improve value in healthcare, we must critically examine the safety of this practice. The freehand method poses the risk of inaccurate placement, leading to multiple placement attempts, injury to adjacent brain parenchyma, and tract hemorrhage. In turn, these procedural complications increase the likelihood of catheter occlusion, malfunction, and infection. Inaccurate placement has been documented to be as high as 40%–50%. Some misplacement include accidental cannulation of the contralateral ventricle, but more than 20% of catheter tips are not in the ventricle. Furthermore, radiographic hemorrhage is cited in up to 41% of cases. These complication rates are unacceptably high for patients and providers.

Key challenges to improving bedside ventriculostomy through existing image guidance technology are time requirements for setup, complexity of use, and cost. A fundamental obstacle is that these patients are often awake and not immobilized during the procedure, as opposed to the rigid fixation typically afforded in the operating room when stereotactic registration and navigation are utilized. In addition to these technical issues, neurosurgeons have stated an unwillingness to adopt technology that extends EVD procedure time by more than 10 minutes. This combination of factors has made improvement of these bedside procedures extremely difficult.

Nonetheless, multiple groups are attempting to develop accurate image guidance for this purpose. Recently, there have been demonstrations using augmented reality with wearable glasses or visors to project anatomical reference images onto the patient’s head. While such approaches have potential, the time requirements and low accuracy of these devices are unacceptable for safe translation to patients. For example, as reported in a 2019 paper by Li et al., neurosurgeons in China donned a Microsoft HoloLens to visualize the preoperative CT-generated holograms of ventricular anatomy and performed EVD placement in 15 patients by keeping the catheter aligned with the holographic trajectory. Surgical planning took 13–35 minutes, registration required adhesive markers on the patients’ heads for registration, and registration took 9–35 minutes, amounting to an additional procedural time of 40.20 ± 10.74 minutes. Additionally, the mean target deviation was 4.34 ± 1.63 mm. In Schneider and colleagues’ 2021 demonstration of EVD placement assisted by the HoloLens, the added procedure time was not documented, the mean deviation from the reference trajectory for all attempts was 7.1 ± 4.1 mm, and the rate of missing the ventricle completely was 31.8%. Although these efforts are extremely valuable, the field is still awaiting an easy-to-use, affordable, and rapidly deployable image guidance technology that offers real-time registration and tracking of a moving patient with the capacity to maintain submillimetric accuracy.

Here, we present and validate a novel image registration system (Zeta Surgical Inc.) for fast and accurate stereotactic neuronavigation. The system enables registration by matching the surface map of a patient’s head, obtained using CT scans, to a live stream of 3D images (Fig. 1). The registration algorithm powering this system, called “Snap-Surface alignment,” performs rapidly, dynamically, and with submillimeter accuracy and eliminates reliance on fiducial markers or manual image-to-patient registration. The additional “Real-Track” feature is capable of near-instantaneous and continuous, autonomous correction in the event of patient movement. Our study aims to describe and validate this technology with catheter placement in human cadaveric specimens with the hope that it may be advanced to clinical trials and extrapolated to enhance the accuracy and safety of other stereotactic procedures, especially those that could be performed outside the confines of the operating room in awake, nonimmobilized patients.

**Methods**

**Registration System**

We engineered a bedside system for pinless and marker-less navigation incorporating two algorithms: one used to perform an initial registration using a global point cloud (termed “Snap-Surface”) and a second that continuously and in real time readjusts with high accuracy the alignment throughout the procedure (termed “Real-Track”; Fig. 1A and B). Both algorithms utilize a surface-based approach that synchronizes a patient’s CT image data with a 3D video feed of the patient’s face.

The CT surface is obtained by segmenting each CT scan as a volumetric voxel field using a density-based filter, which is then converted into a 3D mesh using the 3D Slicer program. This mesh is then converted into a point cloud using the Zeta Surgical software by sampling over 2,000,000 unique points across the mesh’s surface. The 3D video stream of the patient’s face is obtained using a high-accuracy parallel structured light 3D camera (MotionCam-3D M, Photoneo s.r.o.). The 3D camera directly outputs the point cloud needed for the system to perform registration from a generated face depth map. The Snap-Surface and Real-Track algorithms use an artificial intelligence model to scan both CT and 3D camera image point clouds and perform an alignment based on areas of high similarity. The Snap-Surface algorithm’s initial registration takes 3–5 seconds to perform, whereas the Real-Track algorithm continuously adjusts the registration at a rate of up to 10 frames per second.
Hardware Development

The portable system combines a MotionCam-3D M camera with the Polaris Vicra optical position sensor (Northern Digital Inc.) colocated in a single arm with a drape holder (Fig. IC–F). The arm is attached to a cart (GCX Medical Mounting Solutions, GCX Corp.) that includes a screen as the user interface and a personal computer running the software (Windows 10 64-bit OS on an AMD Ryzen 2990WX 32 core central processing unit [CPU], Nvidia RTX 3090 Ti graphics processing unit [GPU], and 72 GB RAM).

The experimental catheters were manufactured to be the same diameter of a traditional EVD using radio-opaque materials in order to visualize them on postprocedure CT scans (polytetrafluoroethylene [PTFE] plastic rod inside a DragonPlate carbon fiber tube). The handheld optical tracker was custom-made with MIC-6 aluminum cast and Vicra position sensors and was designed to allow for easy catheter loading and detachment. To secure the catheters in position after placement within the cadavers, a set of custom cranial bolts were designed to be fitted into a burr hole and included a movable hollow stem (through which the catheter was inserted) in a ball-and-socket configuration with a lockable thumbscrew, which was used to fix the angle and depth of the catheter. The bolts were fabricated on an Objet30 (Stratasys) inkjet-based 3D printer from VeroClear (RGD810) resin.

Specimen Preparation and Imaging

Five formalin-fixed cadaveric heads were used to validate the accuracy and robustness of the Snap-Surface and Real-Track alignment systems. Prior to catheter placements, preoperative CT images of each cadaver head were obtained from the foramen magnum to the vertex of the head without gantry tilt or contrast at a slice thickness of 0.5 mm with a 512 × 512 resolution. Using the 3D Slicer open-source program,20 we selected 6 intraventricular targets for each specimen.

FIG. 1. Two-step image registration system and surgical procedure workflow. Image registration workflow. Step 1 (A): initial Snap-Surface alignment. 1) CT or MRI data and 2) facial depth map are obtained from a patient. 3) The patient’s radiographic facial map is segmented from CT or MRI data and converted into a 3D point cloud (orange). 4) The facial depth map from the 3D camera is converted into a second 3D point cloud (green). 5) The Snap-Surface alignment system synchronizes both point clouds to generate a transformation matrix that allows colocalization of CT or MRI data with the patient’s 3D image. Step 2 (B): continuous Real-Track alignment. 6) Using the aligned CT and 3D camera point clouds as a starting point, 7) the 3D camera continuously captures new 3D images of the patient’s face (green), and 8) the Real-Track algorithm uses each new 3D image to update the initial registration. This process is repeated throughout the procedure at a rate of up to 5–10 frames per second. Surgical procedure workflow. Cadaveric head (C) showing three inserted plastic repositionable catheter alignment bolts for changing the instrument’s angular trajectory (left) and a freshly drilled burr hole (right). The specimen (D) was clamped and draped so that the end of the drape was clipped between the 3D camera and the position sensor, so that the face would not be occluded. Preoperative CT scans (E) were aligned to the respective specimens, and the device was used to guide the catheter placements. After the catheter was placed, the alignment bolts (F) were securely locked in their final positions. Figure is available in color online only.
Registration Motions and Conditions

To assess the robustness of our registration system, we obtained depth images of the cadaveric specimens in a variety of test conditions. Specifically, we evaluated the registration with the heads 1) undraped, 2) draped, 3) draped under dim lighting, 4) draped under bright light (135 W), and 5) draped with a second drape occluding the lower jaw (to simulate facial occlusion caused by an endotracheal tube or changes in mouth position; Fig. 2). It was deemed critical to simulate a sterile workflow during the catheter placements, so the heads were draped using a neurosurgical craniotomy drape specifically designed for this purpose, with an adhesive aperture attached to the scalp. The anterior portion of the drape was extended forward and clipped to the navigation system, so that the 3D camera (beneath the drape) could image the face unobstructed and the position sensor (above the drape) could track the catheters being placed in the operative field.

To characterize Real-Track’s ability to register during patient movement and preserve low surface registration errors (SREs) and target registration errors (TREs), the heads were placed in a Mayfield clamp (Integra LifeSciences) used to create controlled, reproducible, and quantifiable movements. The three distinct movement types were as follows: 1) yaw, nose left or right about an axis running up and down; 2) pitch, nose up or down about an axis running from ear to ear; and 3) roll, rotation about an axis running from front to back of the head. This was done by loosening one axis of the Mayfield system at a time and introducing bidirectional motion in that plane (Fig. 2). Each motion was performed using a lower velocity (maximum velocity: approximately 1–2 cm/sec) and a higher velocity (maximum velocity: approximately 3–4 cm/sec).

Catheter Placement

Catheter placement was performed with surgical draping under ambient light. In each specimen, 3 burr holes were constructed in the general area of Kocher’s point bilaterally (6 burr holes per head), and the custom cranial bolts were secured into the burr holes. Initial registration was completed by Snap-Surface, and then the head was moved in various pitch, yaw, and roll positions within the Mayfield clamp; Real-Track calculated near-continuous adjustments of the registration during this time, and the head was re-secured in a new, random position for catheter placement. A stylet with an optical tracker was used to match the procedural trajectory with the planned trajectory, which was displayed on a screen. Once the user judged the trajectory was appropriate, the catheter was advanced. The trajectory depth was depicted as colored concentric circles that became smaller as the target was approached. Once the target was reached, the catheters were secured with a drop of cyanoacrylate glue and postoperative CT images were obtained.

Error Calculation

To determine the quality of registration, we calculated two key metrics: SRE and TRE. The SRE was calculated by averaging the distances between each point in the CT scan with its corresponding point on the head, as reported by its 3D image. For a given placement, the TRE was defined as the distance between the instrument tip and the position of the intraventricular target as seen on the post-
operative CT scan. The 3D coordinates of each catheter tip were determined using 3D Slicer, and the 3D coordinates of the intraventricular target aligned to the specimen using the registration system were reported by our device. Prior to each alignment, the head and the device were moved to a new position, and the placements were performed with the Real-Track system enabled to account for small movements. After the last catheter placement in each specimen, the head was moved following the slow and fast yaw, pitch, and roll motions. To determine the TRE during head movement using Real-Track, our device calculated the position of the catheter throughout the controlled motions. These catheter positions were then compared to the catheter tip as seen on the postoperative CT scan.

To evaluate the device’s ability to integrate into clinical care, we determined the user error for each placement, which measured the user’s ability to follow the placement instructions as displayed in the user interface. The user error was determined by calculating the distance between the preselected intraventricular catheter and the final position of the catheter as reported by our device.

### Statistical Analysis

Statistical analyses were performed using the SciPy Python library, and plots were generated using the Seaborn Python library (Michael Waskom). S2I distances were calculated using the Zeta library in C++ and rendered using CloudCompare, and TRE was calculated using 3D Slicer. A p value < 0.05 was considered statistically significant.

### Results

#### Baseline SRE

The SRE was calculated for each cadaver head and was obtained with submillimeter accuracy. The overall mean (± standard deviation) baseline SRE when the specimens were undraped was 0.589 ± 0.125 mm (99% CI 0.445–0.733). Despite case-specific deviations from ideal scans or anatomy, the algorithms’ ability to discard areas of low similarity between the CT and the 3D image during the registration preserved a low SRE across specimens.

#### Differential Draping and Lighting Conditions

The algorithms demonstrated an ability to perform under multiple varied procedural conditions (Fig. 2). There was no statistically significant difference in SRE when the specimens were draped or fully undraped; SRE with draping was 0.678 ± 0.149 mm (99% CI 0.506–0.850, p = 0.336; Fig. 3, Supplementary Table 1). Compared with baseline surgical draping, adding bright light under the drape had no statistically significant effect on SRE (p = 0.742); a dimly lit environment also did not impact SRE (p = 0.859). Moreover, compared with baseline draping, occlusion of the lower face did not significantly affect SRE (p = 0.239).

#### Registration Accuracy During Head Movement

To evaluate Real-Track’s ability to maintain low TRE and SRE during patient movement, a series of controlled motions were utilized to explore how TRE evolved during these motions. The 5 specimens were moved following a roll, pitch, and yaw motion, which were performed at both a lower velocity and a higher velocity (actual velocities in cm/sec listed in Supplementary Table 2). Real-Track’s algorithm was tuned to find an ideal parameter set that would enable it to maintain a stable, low TRE while simultaneously minimizing the algorithm’s runtime.

The TRE across motions and velocities was approximately millimetric (Fig. 4, Supplementary Fig. 1, Supple-
The lowest TRE was observed in the pitch motion (slow 0.851 ± 0.234 mm, high 0.855 ± 0.232 mm), whereas the highest TRE was observed in the yaw motion (slow 1.192 ± 0.410 mm, high 1.189 ± 0.382 mm). Across the three motions, there was no significant difference in TRE when the specimens were moved following the slow or fast motion (Supplementary Table 4).

We repeated the same analysis quantifying SRE during the three motions and two velocities and again saw no significant difference when the specimens were moved following the slow or fast motion (Fig. 5, Supplementary Fig. 2, Supplementary Table 5). The SRE was approximately 0.5 mm across motions and conditions, with the lowest SRE being observed in the case of pitch motion (slow 0.851 ± 0.234 mm, high 0.855 ± 0.232 mm), whereas the highest SRE was observed in the roll motion (slow 0.509 ± 0.043 mm, high 0.510 ± 0.043 mm).

### Catheter Placement Error

All 30 catheters were placed with specimens draped to simulate sterile technique under standard lighting (not bright or dim) with mean submillimeter accuracy (Fig. 6, Supplementary Fig. 3). The overall mean SRE for the catheter placements was 0.429 ± 0.108 mm (99% CI 0.378–0.480; Fig. 3, Supplementary Table 6). The mean TRE for the catheter placements was 0.862 ± 0.322 mm (99% CI 0.711–1.013; Fig. 6, Supplementary Table 7). The mean user error (i.e., on the user interface, the error between the user’s target placement location and their final placement position) was 1.674 ± 1.195 mm (99% CI 1.058–2.290; Supplementary Table 8).

### Discussion

Accurate and efficient registration of image guidance software for mobile subjects remains a challenge across surgical fields and specifically in neurosurgery. Motivated by these limitations, we employed computer vision–based technology to develop an image registration algorithm that fuses subjects’ CT scans to respective 3D camera images (Snap-Surface) in combination with an artificial intelligence–driven recalibration for tracking patient movement in real time (Real-Track). Registration and tracking of cadavers were tested during a series of controlled movements and under various surgical conditions, including multiple surgical draping and lighting settings. Using this approach, we demonstrated submillimetric TREs and SREs and a recalibration time of less than a quarter of 1 second, enabling catheter placements with millimetric accuracy.

This approach differs from previous systems proposed for improving EVD placement in several key aspects. For example, in previous studies employing electromagnetic systems (e.g., Smart Stylet, Brigham and Women’s Hospital; or AxiEM, Medtronic), registration (which is sus-
ceptible to distortion by external magnetic fields) requires the user to select points on the patient and accept or redo registration, all resulting in additional time delays.23–25 Furthermore, the electromagnetic systems have a higher error rate, with an average error between 3 and 5 mm.25 This added workflow time and concerns about accuracy have led to few adopters of these systems.16 Other groups have advocated the use of fiducial CT markers to improve spatial and temporal registration efficiency.26,27 However, this approach poses its own set of challenges, including the need to obtain additional CT scans of the patient specifically dedicated to the registration effort. Placement of deep brain stimulation electrodes is one such example in which this technology has an advantage over current frame-based or frameless methods, which require additional CT scans and fiducial markers. In an emergency setting, rescanning a patient is difficult, does not fit well into established workflows, and adds cost, radiation exposure, and delays in care that may be unsafe for a potentially medically unstable patient.

As mentioned in the introduction, new technologies employing augmented reality or virtual reality are intriguing, but registration often requires a fixed marker that must be placed within the sterile field, and that marker must remain at a constant 3D distance from the patient.15,19,28 Furthermore, the processing speed of technologies like HoloLens has had difficulty recalibrating for rapid and/or subtle movements that a patient may make during the procedure. Finally, these innovations demand millimetric or submillimetric accuracy. In the recent HoloLens demonstration by Schneider et al., the mean deviation from the reference trajectory for all attempts was 7.1 ± 4.1 mm, and 31.8% of trajectories missed the ventricle completely.15 To change practice and ensure technology adoption, this accuracy must be higher. Unfortunately, these technologies, which are intended for consumer use in the entertainment space, simply do not demonstrate the millimetric accuracy that is required for healthcare applications.

In our cadaveric study, Real-Track allowed for motion tracking recalibration in under 0.23 seconds, with a mean TRE of 0.862 ± 0.322 mm for the catheter placements and mean user error of 1.674 ± 1.195 mm for the placements. This is the level of accuracy required for cerebral interventions, in which any deviation from precision can create complications with a high risk of morbidity and mortality. Regarding total added time to a procedure, Snap-Surface registration itself takes only 3–5 seconds, so the additional procedure time would involve the time of transferring hospital images from a scanner or PACS onto the Zeta Surgical computer, similar to current navigation systems, which can occur via internet, universal serial bus (USB), or other methods.

The potential to improve cranial navigation for bedside procedures using 3D image registration systems, such as the one described here, could significantly enhance the process of intracranial pressure management in the acute

FIG. 5. Real-Track SRE during motion. SRE during head movement at different velocities and motions, specifically slow and fast pitch motions (A), slow and fast yaw motions (B), and slow and fast roll motions (C). Figure is available in color online only.
setting. Not only would this approach facilitate safe placement of the original EVD catheter, but the enhanced reliability of precise and accurate placement could increase opportunities for subsequent intraventricular and intracranial interventions. In other words, an inaccurately placed catheter can negate any future intervention. For example, in the randomized controlled trials of intraventricular thrombolytic therapy in which recombinant tissue plasminogen activator was used to treat intraventricular hemorrhage, patients incurred a tract hemorrhage at a rate of 23% and 30% of catheters did not terminate in the desired location.12,29,30 Results such as these demonstrate that the absence of techniques for ensuring reliable EVD placement can pose limitations on the ability to run trials or provide necessary patient care without confounding factors or risk.12

It is plausible that this technology could also facilitate interventions such as stereotactic needle biopsies or electroencephalography electrode placement or could be extrapolated to other procedural fields facing a similar challenge of image registration on mobile patients. Furthermore, the technology allows for the active tracking of mobile, nonfixated, and nonanesthetized patients, which could expand our opportunities and reduce our requirements and limitations on when, where, and how neurosurgical interventions are performed.

This tool may also have broader workforce implications. If the technology enables safe and accurate EVD placement, it could expand the emergency intervention of EVDs to nonneurosurgeons in settings in which these lifesaving procedures are often unavailable to patients in need—in both high- and low- and middle-income countries. Presently, regardless of whether one is in a less developed nation or in a rural area within a highly developed nation, countless patients with acute hydrocephalus are admitted to hospitals without neurosurgical staff. Thus, the necessary intervention may be delayed by hours or days—time that may result in irreversible brain injury. However, if technology allows for reliable, precise, accurate guidance for intervention, it is conceivable that staff with baseline procedural training may be able to perform ventriculostomy as a temporizing measure prior to transport to a neurosurgical center.

Despite the many advantages offered through the approach described here, the limitations of this study warrant further discussion. The CT scanning protocol used in the study was relatively standard, with 0.5-mm-thick slices spanning the foramen magnum to vertex and inclusion of the patient’s face anteriorly. Slice thickness can be variable; however, institutional protocols may need to be modified to ensure the patient’s face is included within the scan. Additionally, the registration algorithm presented does not necessarily account for deformations that may occur on the patient’s surface between the time of CT data acquisition and that of active 3D image registration. However, with the drape occlusion study, we showed that changes to the lower portion of the face, as may be expected with intubation, do not introduce significant error. The artificial intelligence algorithm’s capacity to trim low similarity areas appears to resolve many of these circumstances, and this accuracy holds even in the extreme settings of differing draping and lighting. Given that patient’s soft tissues will have more plasticity than formalin-fixed cadaver tissue, we intend to assess this potential source of error when translating into patients.

In all systems utilizing artificial intelligence algorithms, there is complexity that can be computationally demanding and require substantial computing power. Improvements in computational efficiency of the algorithm and in the hardware will improve registration speed, as well as reduce its computational requirements, allowing for more economical devices, and thus drive the development of smaller and more portable neuronavigation systems. A small, built-in screen on the handheld optical tracker used to advance the catheter is currently in testing and would allow the surgeon to perform the catheterization without removing his or her eyes from the surgical field. This system optimization is ongoing as we prepare for human clinical trials.

To our knowledge, this is the first practical demonstration of neuronavigation for mobile patients using frameless, marker-less, surface registration and real-time tracking with computer vision technology. Studies were performed in clinically relevant settings with sterile draping, variable head movements, and differential lighting, and cadaveric ventriculostomy was completed with high accuracy and low user error. Going forward, we plan to improve the overall efficiency of the algorithm to further enhance registration speed and reduce computational requirements, with a vision of the processor as a handheld device. We are also working to launch this technology in human clinical trials with the hope of positively impacting the standard of care for bedside neurosurgical interventions. In the more distant future, this technology could
be applied for other neurosurgical procedures, including brain biopsy, and adjacent procedural fields. We owe it to our patients to continue raising the bar on safety and accuracy in the care we deliver.

Conclusions
This computer vision–based registration system provided real-time tracking of cadaveric heads with a recalibration time of less than 0.25 seconds with submillimeter accuracy and enabled catheter placements with millimetric accuracy. Using this approach to guide bedside ventriculostomy could reduce complications, improve safety, and be extrapolated to other frameless stereotactic applications in awake, nonimmobilized patients.

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References

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Supplemental Information
Online-Only Content
Supplemental material is available with the online version of the article.

Previous Presentations
Preliminary data on surface registration were accepted for presentation at the 2020 Annual Meeting of the Congress of Neurological Surgeons.

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