NextLens—The Next Generation of Surgical Navigation: Proof of Concept of an Augmented Reality System for Surgical Navigation

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Abstract

Objective The aim of this work was the development of an augmented reality system including the functionality of conventional surgical navigation systems.

Methods An application software for the Augmented Reality System HoloLens 2 from Microsoft was developed. It detects the position of the patient as well as position of surgical instruments in real time and displays it within the two-dimensional (2D) magnetic resonance imaging or computed tomography (CT) images. The surgical pointer instrument, including a pattern that is recognized by the HoloLens 2 sensors, was created with three-dimensional (3D) printing. The technical concept was demonstrated at a cadaver skull to identify anatomical landmarks.

Results With the help of the HoloLens 2 and its sensors, the real-time position of the surgical pointer instrument could be shown. The position of the 3D-printed pointer with colored pattern could be recognized within 2D-CT images when stationary and in motion at a cadaver skull. Feasibility could be demonstrated for the clinical application of transsphenoidal pituitary surgery.

Conclusion The HoloLens 2 has a high potential for use as a surgical navigation system. With subsequent studies, a further accuracy evaluation will be performed receiving valid data for comparison with conventional surgical navigation systems. In addition to transsphenoidal pituitary surgery, it could be also applied for other surgical disciplines.

Keywords
- augmented reality
- surgical navigation
- transsphenoidal pituitary surgery
- computer-assisted surgery

Introduction

Surgical navigation systems are an essential tool for surgeries that require high precision.[1–3] They provide exact intraoperative position tracking of surgical instruments on the basis of preoperative computed tomographic (CT)/magnetic resonance (MR) datasets. This allows operations to be performed more safely, and it has been a concept that has been established in neurosurgery for over 20 years. The reason for this is that the bony skull provides secure and unchangeable reference points.

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The accuracy of conventional navigation systems has been investigated in various studies and tests.

A knee surgery (reconstruction of the anterior cruciate ligament) was performed by Kim et al in 2017 using a surgical navigation system on phantoms and cadavers.[4] This showed an accuracy of 0.24 ± 0.03 mm on the phantom and 0.9 mm on the cadaver/body donors.

In the same year, Hung et al published a pilot study on the placement of an implant in the zygomatic bone.[5] Using a real-time surgical navigation system, the accuracy of entry and exit sites was determined. The results were in a similar range to each other, but the entry deviation of 1.35 ± 0.75 mm was slightly lower than the exit deviation of 2.15 ± 0.95 mm.

In neurosurgery procedures, measurements of navigation system accuracy were also investigated. In 2014, the Deng et al research group published a study on the use of neuronavigation with the use of a wireless tablet PC.[6] For this purpose, in addition to a preclinical study on the skull, a clinical study on the resection of an intracranial tumor was performed on three patients. The accuracy or deviations were approximately 1.6 mm for the skull phantom study and approximately 2.1 mm for the clinical experiment.

Disadvantages of conventional surgical navigation systems have been analyzed by different research groups.

The navigation systems most commonly used during surgery are optical systems. In optical navigation systems, a camera recognizes special markers that are located directly at the patient and on the surgical instruments. Direct visual contact between the camera and markers is essential. Problems with maintaining line of sight with optical systems during surgery is well recognized.[7] The position of the patient and the instrument in space is calculated by triangulation. The optical systems are divided into passive and active systems. In passive systems, the camera emits infrared light, which is reflected by the markers and detected by the camera.[1–3,8] Active systems, on the other hand, have light-emitting diodes as markers, the light of which is recognized by the camera.[9–11] Both systems require a time-consuming registration process to transfer the patient's preoperative imaging to the system and link the patient's position to the imaging and instruments in a uniform coordinate system.

The main disadvantages of current system solutions available on the market are:

- High investment and maintenance costs.
- Poor/impractical microscope integration.
- Complex/time-consuming operation.
- Enormous space requirements in the operating room.
- Line of sight problem.
- Time-consuming registration process.

Enhancements under development include applications of data glasses, which enable the use of augmented reality (AR) during the operation. Virtual anatomical structures of the patient are displayed in the surgeon's field of vision, comparable to the head-up display in a car.[12–15] However, only anatomical three-dimensional (3D) structures are displayed. Surgical instruments are not recorded automatically, and their position is not displayed on the two-dimensional (2D) cross-sectional images of CT/MRI with crosshairs for better orientation in real time.

In transsphenoidal pituitary surgery, the application of surgical navigation is very important to identify the position of the carotid artery and the pituitary.[16,17]

The aim of this work was to counter previously mentioned limitations and to make navigation available as an indispensable tool for many surgical disciplines and users. As a first clinical application, transsphenoidal pituitary surgery was selected to demonstrate the proof of concept of an AR-based surgical navigation system.

Materials and Methods

Augmented Reality System

The data glasses HoloLens 2 with its 3D- and 2D-sensors (Microsoft, Redmond, United States) was selected as the technological base for our navigation approach (►**Fig. 1**). An artificial intelligence algorithm was developed so that the face of the test subject could be automatically detected by sensors of the HoloLens 2. Furthermore, the registration of the different coordinate systems HoloLens 2, magnetic resonance imaging (MRI), test subject, and surgical instrument can be performed automatically. The user-specific defined menu structure was created in close collaboration with experienced surgeons.

The following workflow pipeline was established with the procedure:

- Segmentation of MRI/CT data.
- Postprocessing and export as 3D STL-file to the HoloLens 2 (**S**urface **T**esselation **L**anguage).
- Automatically registration of MRI/CT, Patient, HoloLens 2, and surgical instrument.
- Projection of the 2D- MRI/CT slices in the surgeon's view inside the HoloLens 2 comparable with the head-up display of a car.
- Display of the real-time position of the surgical instrument with the crosshair within the 2D- MRI/CT slices.

Surgical Pointer Instrument

The handpiece of the pointer was designed with CAD-Software Autodesk Fusion 360 (Autodesk, San Rafael, United States). In a previous work, the ergonomic design was already evaluated by an experienced skull base neurosurgeon.[18] The handpiece was combined with a cuboid tracker. A special-colored test pattern was placed on each cuboid surface so that the instrument could be recognized by the sensors of the HoloLens 2 (►**Fig. 2**). With the help of the Multi Jet Fusion 3D-printing technology (HP Inc., Palo Alto, United States), the surgical instrument with colored pattern was transferred from the virtual world into the real world. The biocompatible and steam-sterilizable material Polyamide-12 was applied. After 3D-printing, a stainless steel cylinder of 100 mm length for indicating points of interest at the test subject was connected with the handpiece and the cuboid tracker. The colored pattern was identified with the software engine for AR Vuforia.[12]

Fig. 1 Realistic test scenario inside an operating room. The surgeon interacts with his fingers through the menu of the navigation software.

Surgical Test Scenario

The complete cadaver head was scanned with an CT including the skull base. Testing was performed in a real operating setup to realize realistic conditions, i.e., ceiling mounted lights and position of surgeon and patient. The surgeon positioned the HoloLens 2 on his head and started the application software.

As the geometry of the complete instrument is part of the navigation software, the tip of the cylinder is displayed as crosshair inside the 2D-CT image projected in the HoloLens

Fig. 2 The surgeons moves the surgical pointer to the points of interest at the patient. The colored pattern on the cuboid tracker is detected by the sensors of the HoloLens 2.

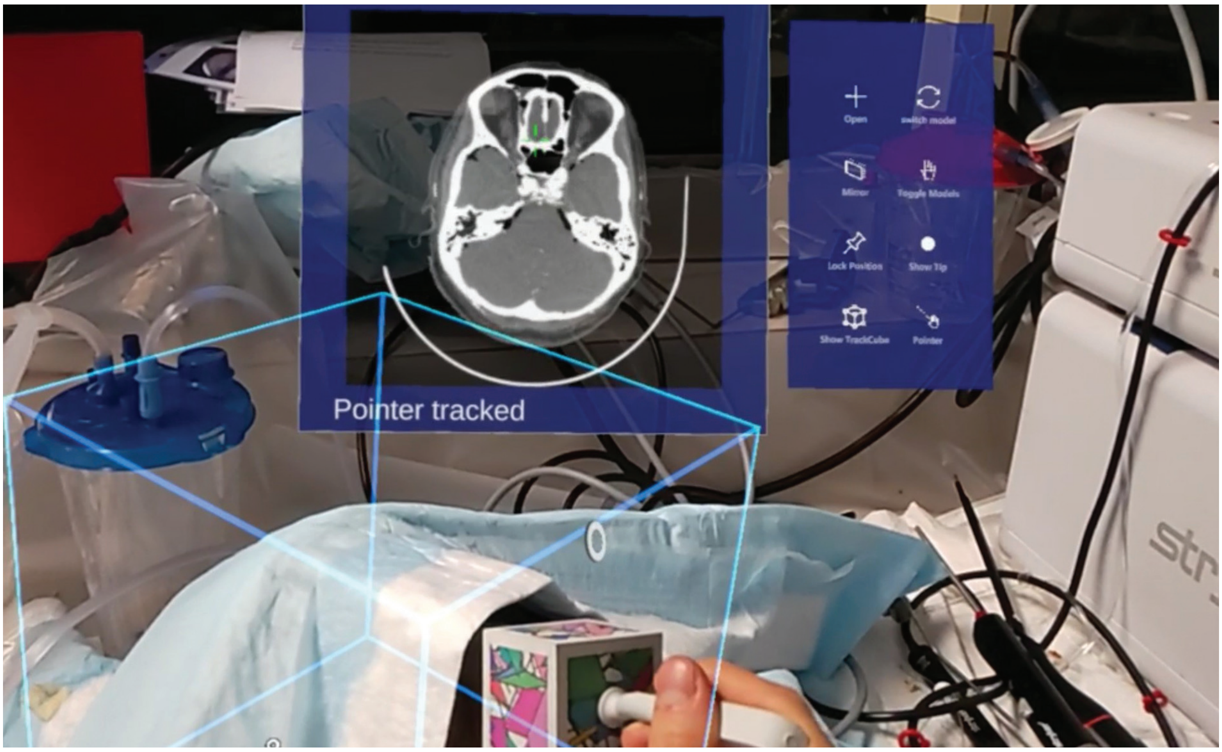

Fig. 3 Surgeon's view through the HoloLens 2. Setup with a cadaver skull to perform a transsphenoidal pituitary surgery. Computed tomography coronal slice with the real-time position of the surgical pointer.

2. If the instrument was moved, the 2D-CT images that was projected in the field of view was updated all the time, i.e., the surgeon could see the corresponding slice according to the real position of the surgical instrument.

The instrument was moved and held in a position, which is typical within transsphenoidal pituitary surgery to display the pituitary gland and the sphenoid sinus on the coronal CT image. The real position of the instrument was evaluated with an endoscope and compared with the displayed position in inside the 2D-CT image. The left and right carotid artery as well as the rear wall of the sphenoid sinus were used as anatomical landmarks.

Within a second experimental setup, a cadaver head with the corresponding MRI scan was applied to evaluate the accuracy. As anatomical landmarks, the inner corner and the outside angle of the left and right eye as well as the nasion were considered. Every measurement position was repeated 15 times. When the navigated pointer was placed in the target position at the anatomical landmark, a screenshot of the corresponding MRI was recorded. With the help of the software Dicom2Print the distance between the center of the crosshair indicating the tip of the navigated pointer and the anatomical landmark inside the MRI scan was measured.

Results

Augmented Reality System with Surgical Test Scenario

With the help of the HoloLens 2 and the developed software application, proof of concept of the augmented surgical navigation system could be demonstrated within a realistic operating room environment simulating the transsphenoidal pituitary procedure. It was possible to identify the surgical pointer instrument inside the same coordinate system as the cadaver skull without any additional time-consuming registration procedure using several anatomical landmarks (►**Fig. 3**). The instrument could be moved inside the cadaver skull and its position was continuously detected by the sensors of the HoloLens 2.

The left and right carotid artery as well as the rear wall of the sphenoid sinus as anatomical landmarks could be displayed and indicated with a crosshair within the 2D-cornal CT images projected onto the surgeon's view inside the HoloLens 2. If the surgical pointer was moved, the displayed coronal CT slice was updated in real time and the slice corresponding to the current instrument position was visualized.

The representation of the corresponding CT image was possible in real time. No delay was recognized by the surgeon when the navigated pointer instrument was positioned at the anatomical landmark.

Within the second experimental setup following distances between actual position at the cadaver skull and displayed position of the instrument's tip inside the MRI were measured (►**Table 1**, ►**Fig. 4**).

Surgical Pointer Instrument

It could be shown that the surgical pointer instrument can be created with a colored pattern with the HP Multi Jet Fusion 3D-printing technology. The geometrical dimension of the cuboid tracker with the colored pattern was sufficient to ensure a reliable detection with the sensors of the HoloLens 2. The light conditions that are normally used during surgery

Table 1 Distance between actual and displayed position of the instrument's tip inside the magnetic resonance image

Nr.	Left eye		Right eye		Nasion
	Inner corner	Outside angle	Inner corner	Outside angle	
Mean	1.04	1.20	1.14	1.21	1.18
SD	0.55	0.47	0.46	0.51	0.50
Max.	1.84	1.81	1.97	1.91	1.93
Min.	0.26	0.11	0.28	0.41	0.42

Abbreviations: Max., maximum; Min., minimum; SD, standard deviation.

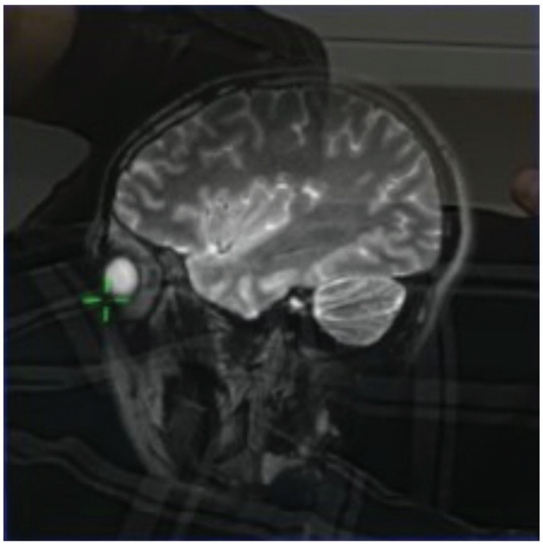

Fig. 4 Superimposed representation inside the CAD-software. Corresponding magnetic resonance image with the right eye and the measuring point.

inside the operating room didn't influence recognition of the instrument.

The 3D-printing material Polyamide-12 guarantees a safe application inside the operating room at the patient due to its biocompatible property. Furthermore, it can be steam sterilized, which is the standard sterilization method in every hospital.

Discussion and Conclusion

The application of data glasses such as the Microsoft HoloLens 2 for displaying AR has great potential for augmenting surgical navigation systems for multiple surgical disciplines. In contrast to the current AR-systems, the new approach would make it possible to use the HoloLens 2 as a surgical navigation system, with the patient surface being recorded in real time using the integrated sensors for automatically registering with the medical image data.

A limitation of the workflow pipeline is the time-consuming segmentation process of the CT data and the postprocessing of the virtual 3D-model to transform it to the HoloLens 2.

During the placement of the instrument with the AR navigation, the recognition of the graphical marker was not all the time stable. The consequence of this is the redesign of the marker so that it can be reliably recognized from all angles. Additionally, tests are also performed with ArUco markers.[19,20]

Our results with (1.04 ± 0.55) mm for the highest and with (1.21 ± 0.51) mm for the lowest accuracy seems to be very promising to continue the development for a future application at patients. The main limitation factor is the layer thickness of the medical imaging, which is usually 1 mm.

In 2021, the research group around Pérez-Pachón et al described the accuracy of HoloLens based on a nonclinical study using different markers.[21] They found that the use of small markers resulted in a larger error than comparatively larger markers. Furthermore, they found that the position of the markers was crucial, as distances varied in addition to the inaccuracies of the holographic representation of the points. Within the study, it was revealed that central marker positions could be mapped more accurately than the lateral markers (0.6 ± 0.3–0.9 ± 0.55 mm). Distance measurements had a deviation of 2.4 ± 1.8 mm.

In van Doormaal et al 2019, a study was performed on both phantoms and patients to compare the accuracy of HoloLens with conventional navigation systems (kN).[22] For this, 10 plastic heads were examined in a phantom study. Subsequently, three patients with different clinical pictures were treated in a small clinical study. It was found that the holographic representation had an accuracy of 7.2 ± 1.8 mm (cf. kN: 1.9 ± 0.45 mm; −5.3 mm) for the plastic heads and 4.4 ± 2.5 mm (cf. kN: 3.6 ± 0.5 mm; −0.8 mm) for the three patients.

This study was also addressed by the research group led by Scherl et al in 2021. The aforementioned group thereby examined the accuracy of the HoloLens without and with the use of the surgical navigation system of the company Fiagon.[13] Here it was found that the deviation of the HoloLens in terms of matching the holographic points with the real ones was 12.4 mm. However, it should be mentioned here that the accuracy improved in the course of using the HoloLens. For example, the accuracy was 13.26 mm at the beginning and 10.06 mm at the end.

In Zhou et al 2022, the treatment of hypertensive intracerebral hemorrhage was studied using HoloLens and specially designed navigation instruments on both a phantom and 10 patients.[23] It was found that the average registration error, i.e., the deviation in performing surgery, was 1.03 mm on the phantom and 1.94 mm within the clinical trial.

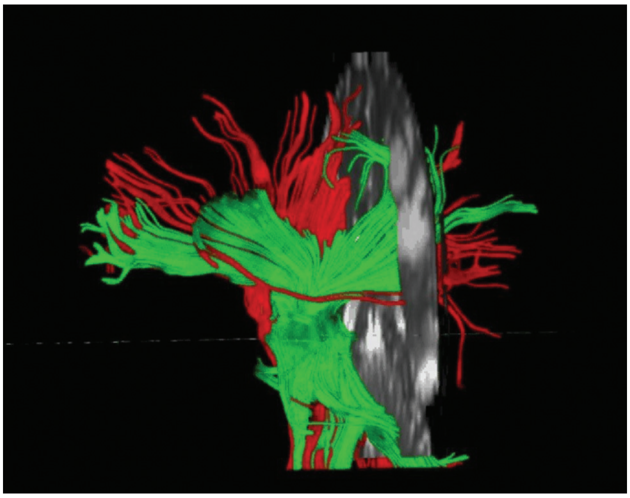

Fig. 5 Additional patient information such as diffusion tensor Image can also be included inside the surgeon's view through the HoloLens 2.

As we used for our experiment a cadaver skull, we could not evaluate how body fluids can effect the tracking. This has to be considered within the next experiments.

The duration with one battery load is about 3 hours and can be extended with external battery packs.

Theoretically, the HoloLens 2 could be integrated in conventional navigation systems, but our approach is to provide AR navigation systems also for smaller hospitals with lower budget for investments.

As a next step, further measurement of the accuracy of our system is required to objectively compare our augmented surgical navigation system with conventional ones. An additional system component will be segmentation and planning software. Based on artificial intelligence methods, relevant anatomical structures should be automatically segmented within a few minutes. Based on the target structure, the surgeon could then plan surgical approaches. Additionally, functional patient data, e.g., diffusion tensor image data, could be visualized inside the navigation system (►**Fig. 5**).

Due to the platform technology, this concept has the potential to reduce costs of navigation systems considerably with a significant expansion of applications.

Authors' Contributions

R.G., D.W., C.S.: technical idea, writing of manuscript; M. B., L.A.: software instrument tracking; P.G.: design of surgical pointer, review of manuscript; F.K.: segmentation CT, construction of surgical pointer; E.G., R.M., S.S.: review of manuscript.

Ethics Approval

No ethical approval was required. The cadaver skull was applied according to the Declaration of Helsinki.

Consent to Participate

The cadaver skull was applied according to the declaration of Helsinki.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author, upon request.

Conflict of Interest

None declared.

References

1 Amundson M, Newman M, Cheng A, Khatib B, Cuddy K, Patel A. Three-dimensional computer-assisted surgical planning, manufacturing, intraoperative navigation, and computed tomography in maxillofacial trauma. Atlas Oral Maxillofac Surg Clin North Am 2020;28(02):119–127

2 Bergeron L, Bouchard S, Bonapace-Potvin M, Bergeron F. Reply: intraoperative surgical navigation reduces the surgical time required to treat acute major facial fractures. Plast Reconstr Surg 2020;146(04):509e–510e

3 Demian N, Pearl C, Woernley TC III, Wilson J, Seaman J. Surgical navigation for oral and maxillofacial surgery. Oral Maxillofac Surg Clin North Am 2019;31(04):531–538

4 Kim Y, Lee BH, Mekuria K, et al. Registration accuracy enhancement of a surgical navigation system for anterior cruciate ligament reconstruction: a phantom and cadaveric study. Knee 2017; 24(02):329–339

5 Hung K-F, Wang F, Wang H-W, Zhou W-J, Huang W, Wu Y-Q. Accuracy of a real-time surgical navigation system for the placement of quad zygomatic implants in the severe atrophic maxilla: a pilot clinical study. Clin Implant Dent Relat Res 2017;19(03):458–465

6 Deng W, Li F, Wang M, Song Z. Easy-to-use augmented reality neuronavigation using a wireless tablet PC. Stereotact Funct Neurosurg 2014;92(01):17–24

7 Mehbodniya AH, Moghavvemi M, Narayanan V, Waran V. Frequency and causes of line of sight issues during neurosurgical procedures using optical image-guided systems. World Neurosurg 2019;122:e449–e454

8 Ewurum CH, Guo Y, Pagnha S, Feng Z, Luo X. Surgical navigation in orthopedics: workflow and system review. Adv Exp Med Biol 2018;1093:47–63

9 Tschopp KP, Thomaser EG. Outcome of functional endonasal sinus surgery with and without CT-navigation. Rhinology 2008;46(02): 116–120

10 Briem D, Linhart W, Lehmann W, et al. Computer-assisted screw insertion into the first sacral vertebra using a three-dimensional image intensifier: results of a controlled experimental investigation. Eur Spine J 2006;15(06):757–763

11 Akca F, Schwagten B, Theuns DAJ, Takens M, Musters P, Szili-Torok T. Safety and feasibility of single-catheter ablation using remote magnetic navigation for treatment of slow-fast atrioventricular nodal reentrant tachycardia compared to conventional ablation strategies. Acta Cardiol 2013;68(06):559–567

12 Frantz T, Jansen B, Duerinck J, Vandemeulebroucke J. Augmenting Microsoft's HoloLens with Vuforia tracking for neuronavigation. Healthc Technol Lett 2018;5(05):221–225

13 Scherl C, Stratemeier J, Karle C, et al. Augmented reality with HoloLens in parotid surgery: how to assess and to improve accuracy. Eur Arch Otorhinolaryngology 2021;278(07):2473–2483

14 Shi L, Luo T, Zhang L, et al. Preliminary use of HoloLens glasses in surgery of liver cancer. Zhong Nan Da Xue Xue Bao Yi Xue Ban 2018;43(05):500–504

15 Tepper OM, Rudy HL, Lefkowitz A, et al. Mixed reality with HoloLens: where virtual reality meets augmented reality in the operating room. Plast Reconstr Surg 2017;140(05):1066–1070

16 Koutourousiou M, Gardner PA, Fernandez-Miranda JC, Paluzzi A, Wang EW, Snyderman CH. Endoscopic endonasal surgery for giant pituitary adenomas: advantages and limitations. J Neurosurg 2013;118(03):621–631

17 Zwagerman NT, Zenonos G, Lieber S, et al. Endoscopic transnasal skull base surgery: pushing the boundaries. J Neurooncol 2016; 130(02):319–330

18 Grunert R, Klietz S, Gardner PA, Fernandez-Miranda JC, Snyderman CH. Evaluation of bendable surgical suction devices made of shape-memory alloy for the endonasal transsphenoid removal of pituitary tumors. Ear Nose Throat J 2018;97(12): 413–416

19 Thabit A, Niessen WJ, Wolvius EB, van Walsum T. Evaluation of marker tracking using mono and stereo vision in Microsoft HoloLens for surgical navigation. In:SPIE Proceedings Volume 12034, Medical Imaging 2022: Image-Guided Procedures, Robotic Interventions, and Modeling. San Diego, California, United States; 2022

20 Schuppstuhl T, Tracht K, Henrich D. Annals of Scientific Society for Assembly, Handling and Industrial Robotics. 1st ed. 2020 Berlin, Heidelberg: MHI e.V; 2020

21 Pérez-Pachón L, Sharma P, Brech H, et al. Effect of marker position and size on the registration accuracy of HoloLens in a non-clinical setting with implications for high-precision surgical tasks. Int J CARS 2021;16(06):955–966

22 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(06):588–593

23 Zhou Z, Yang Z, Jiang S, Zhuo J, Zhu T, Ma S. Surgical navigation system for hypertensive intracerebral hemorrhage based on mixed reality. J Digit Imaging 2022;35(06):1530–1543