Augmented reality–assisted roadmaps during periventricular brain surgery

Florian Bernard, MD, PhD,^{1–4} Julien Haemmerli, MD,¹ Gregory Zegarek, MD,¹
Daniel Kiss-Bodolay, MD,¹ Karl Schaller, MD, PhD,¹ and Philippe Bijlenga, MD, PhD¹

¹Division of Neurosurgery, Department of Clinical Neurosciences, Geneva University Hospitals, Geneva, Switzerland; ²Division of Neurosurgery, Angers University Hospitals; ³Laboratory of Anatomy, University of Angers; and ⁴CRCINA, UMR 1232 INSERM/CNRS and EA7315 team, Angers, France

Visualizing major periventricular anatomical landmarks intraoperatively during brain tumor removal is a decisive measure toward preserving such structures and thus the patient's postoperative quality of life. The aim of this study was to describe potential standardized preoperative planning using standard landmarks and procedures and to demonstrate the feasibility of using augmented reality (AR) to assist in performing surgery according to these "roadmaps." The authors have depicted stepwise AR surgical roadmaps applied to periventricular brain surgery with the aim of preserving major cognitive function. In addition to the technological aspects, this study highlights the importance of using emerging technologies as potential tools to integrate information and to identify and visualize landmarks to be used during tumor removal.

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KEYWORDS augmented reality; neurosurgery; periventricular surgery

INTRAAXIAL surgery is facilitated with the aid of neuro-navigation systems.^{1–4} These systems are particularly effective at the beginning of the operation to define the limits of the transcortical approach. However, these systems lose precision and reliability during tumor removal due to the brain shift phenomenon.⁵ As others have argued, the use of neuronavigation systems does not replace solid surgical anatomical knowledge.^{6,7}

During recent decades, augmented reality (AR) has gained popularity, with increasing numbers of applications in the fields of neurosurgery and neuroscience.^{8–11} This computer technology provides a real-time updated 3D virtual model of anatomical details, overlaid on the real surgical field. Recent innovations have increased access to this technology through smartphones, adapted goggles, and operative microscopes.^{12–16}

Intraoperative visualization of major ventricular and periventricular anatomical landmarks during brain tumor removal is critical for their preservation and thus the patient's postoperative clinical outcome. These landmarks include the periventricular vessels, fiber tracts, and the basal ganglia, already described by major anatomical studies.^{17–21} Given the inherent difficulty in direct visu-

alization of these anatomical landmarks during periventricular surgery,²² we sought to explore the possibilities offered by AR technology as a surgical aid to help localize these structures and define standardized surgical procedures. The main purpose of this article is to present a set of AR-assisted microneurosurgical standard procedures, or "roadmaps," illustrated with a series of cases in which the surgical planning and interventions were performed accordingly.

Methods

This study reports on current normal clinical practice.^{8,10,16} It focuses on the AR implementation of stepwise surgical maneuvers during supratentorial intralobar brain surgery. Therefore, the ethics committee found this study exempt from formal review.

Specific nomenclature tailored to AR-assisted surgery has been described in previous publications,^{16,23} including the terms "signature structure" and "target structure." Signature structures are geometric, unique, and unambiguous anatomical structures. They are used to assess navigation precision and eventually may be used to apply navigation

ABBREVIATIONS AR = augmented reality; IFOF = inferior frontooccipital fasciculus; ILF = inferior longitudinal fasciculus.

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TABLE 1. Major surgical periventricular landmarks and their functional role

Approach	Tracked Anatomical Structure	Functional Role	Disconnection Syndrome/ Lesion Syndrome		AR Role
			Lt	Rt	
Frontal	Caudate nucleus ²¹	Bottom up attention (goal directed), memory, learning, sleep, emotion, language ²¹	Bottom up attention (goal directed), memory, learning, sleep, emotion, language ²¹		Target structure
	Fornix ¹⁹	Memory	Anterograde amnesia ¹⁹		Target structure
	IFG (pars opercularis & triangularis) ³²	Language (lt), theory of mind (bilat), visuospatial cognition (rt)	Motor aphasia	Unilat neglect, theory of mind deficit ²⁵	Target structure
	Anterior perforate substance ¹⁸	Corticospinal tract vascular supply	Motor function ¹⁸		Target structure
	Corticospinal tract	Motor pathway	Motor function		Target structure
Temporal	Lateral sulcus ³²				Signature structure
	Vein of Labbé (inferior anastomotic vein)	Temporoparietal drainage			Signature structure
	Optic radiation	Optic pathway	Quadrantanopia/hemianopia		Target structure
	Hippocampus	Memory pathway			Target structure
	Visual word form area	Identifying words	Alexia		Target structure
Occipital lateral	Arcuate fasciculus ³⁰	Language (lt), visuospatial cognition (rt)	Aphasia	Unilat neglect	Target structure
	IFOF ²⁰	Language (lt), visuospatial (rt)	Aphasia	Unilat neglect	Target structure
Parietal superior	Postcentral gyrus ³²	Sensitive pathway	Sensitive function		Target structure
	Lat sulcus ³²				Signature structure
	Parietal operculum ³²	Sensitive pathway	Sensitive function		Target structure
Parietal inferior	Heschl's gyrus ³²				Target structure
	Superior longitudinal fasciculus III	Language (lt), visuospatial (rt)	Aphasia	Unilat neglect	Target structure
	Arcuate fasciculus	Language (lt), visuospatial (rt)	Aphasia	Unilat neglect	Target structure
Insula	Periinsular sulcus				Signature structure
	M ₂ segment				Signature structure
	Lenticular nucleus				Target structure
	Arcuate fasciculus (lat to claustrum)	Language (lt), visuospatial (rt)	Aphasia	Unilat neglect	Target structure
	IFOF (btwn claustrum & putamen)	Language (lt), visuospatial (rt)	Aphasia	Unilat neglect	Target structure

IFG = inferior frontal gyrus.

Reference numbers refer to pertinent articles from the reference list.

updates in a stepwise process using a set of structures identified along the surgical path. Target structures are virtual objects generated through preoperative imaging. Both signature and target structures are defined preoperatively during surgical planning and are visualized intraoperatively using AR. The ventricular and periventricular target structures used in our study were selected as relevant on the basis of the most recent anatomical knowledge. These structures are presented in Table 1.^{17–21}

Patient Population

All patients who underwent surgical treatment of an intracerebral lesion by the AR team between 2019 and 2021 were included. A gross-total resection was planned in each case. The preoperative planning included integration of multiple MR 3D imaging series, including high-resolution T1-weighted imaging with gadolinium injection,

T2-weighted SPACE sequences, time of flight, diffusion tensor imaging, and, when available, CTA. Preoperative and postoperative neuropsychological examinations were performed.

Preoperative AR Planning

Three-dimensional imaging (3D MRI and 3D CTA) was performed during the routine preoperative diagnostic workup. Images were stored in the hospital PACS in DICOM format. The data sets were loaded in the surgical planning tool (Brainlab iPlan and Elements, Brainlab) and merged into a single 3D matrix. Virtual objects were generated systematically by autosegmentation of the skin, bone, cerebral vessels, basal ganglia, eyes, optic nerves, chiasma, optic tracts, brainstem, and ventricles. Other relevant surgical landmarks were generated on a case-by-case basis (Table 1). Segmentation was performed either

FIG. 1. Temporal roadmap using a 2D microscope image injection of the patient's head. **A:** AR registration. Note the perfect alignment of the virtual images with the nose, brow, and cheeks. **B:** Use of target structures to define orientation and optimal head positioning.

by using an automated segmentation tool with pixel intensity threshold-based segmentation in which the user determined the region of interest and the desired range of intensity or density or by manual contour drawing.

Initial AR System Accuracy Check

After patient positioning and operative microscope registration, the AR accuracy was checked. A 3D volume-rendered model of the patient's head was injected into the eyepiece of the navigated microscope so that the virtual image was overlaid on the microscope image, which was aimed and focused onto the patient's head in low magnification. The precision of the overlaid virtual image to the real head was assessed using the nose, eyebrows, and the auricular concha superposition (Fig. 1A). Target structures (Fig. 1B) were then injected for orientation and optimal head positioning. The surgical field and operating microscope were draped; the navigation tracking system tools, or reference stars, were replaced with identical sterile ones, and the microscope calibration was repeated.

Intraoperative Image Injection and Surgical Technique

After incision, the virtual model of the skull was in-

jected, and registration precision was reassessed on a millimetric scale by evaluation of the overlap of the model with the patient's skull at medium magnification.¹⁶ The tumor was then injected to help in craniotomy planning. After opening the dura mater, a 3D semitransparent model of the tumor was injected, and registration was once more reassessed at a submillimetric scale by evaluation of the overlap between the model and the visible vascular signature structure at high magnification (Fig. 2). All AR-assisted techniques were based on surgical basics for lobectomy approaches.⁷

Results

A total of 13 patients (8 women; mean age 49.7 years, range 39–75 years) who underwent surgery with AR were included. The tumor was located in the frontal lobe in 53.8% ($n = 7$) of patients, parietal lobe in 15.4% ($n = 3$), and the temporal lobe, parietooccipital lobe, and insula in 7.7% ($n = 1$) each (Table 2). The lesions were glioblastomas in 84.6% ($n = 11$) of patients, and an anaplastic oligodendroglioma, a grade 2 oligodendroglioma, and a lymphoma in 7.7% ($n = 1$) each. The mean duration of surgery was 4 hours, 30 minutes. We were able to navigate using AR in

FIG. 2. Temporal tumor removal. Using AR, intraoperative injection of the target and signature structures (e.g., visualization of the tumor boundaries) was performed. The surgeon followed the planned temporal roadmap, especially concerning its entry point inside the temporal ventricular horn and its surgical trajectory.

all patients, giving an overall success rate of 100%. The mean time to perform the AR procedure corresponded to 10% of the total procedure time. No complications were encountered during AR navigation. A gross-total resection was performed in 10 patients (76.9%); none of the 13 patients had new neurological deficits postoperatively. The four roadmaps described below were used to design and perform the intracerebral procedures for each patient.

Roadmap for AR-Assisted Frontal Lobe Surgery

For frontal lobe AR-assisted surgery, the target structure to remove was the tumor volume. It was used to guide drawing of the skin incision and the craniotomy and to

orient the surgeon during the transcerebral navigation and dissection. The target structures to be preserved and the signature structures were displayed according to the surgeon's needs at each step of the operation (Fig. 3A and B). At the superficial level, the signature structures visualized on the scalp were the crus of the helix, cymba, cavum, and lacrimal caruncle. After the skin incision, the coronal suture and the bregma were the signature structures that allowed navigation updates. Then, a tailored craniotomy based on the tumoral AR volume was performed, and the dura was opened. Cortical venous vascularization, especially in the precentral area, was useful to recalibrate the navigation. As described in Video 1, important target structures to preserve were the precentral gyrus and the corticospinal tracts.

VIDEO 1. Frontal roadmap overlaid on MR images. **Upper:** probe view; **lower left:** axial view; **lower right:** coronal view. *Purple* is the IFOF; *blue* is the corticospinal tract; and *red* is the arcuate fasciculus. Volume: surgical roadmap. Temporal roadmap overlaid on MR images. **Left:** coronal view; **right:** axial view. *Yellow* is the visual pathway; *green* is the ILF; *purple* is the IFOF; *blue* is the corticospinal tract; and *red* is the arcuate fasciculus. Volume: surgical roadmap. Occipital roadmap overlaid on MR images. **Upper left:** coronal view; **upper right:** probe view; **lower left:** sagittal view; **lower right:** axial view. *Yellow* is the visual pathway; *green* is the ILF; *purple* is the IFOF; *blue* is the corticospinal tract; and *red* is the arcuate fasciculus. Volume: surgical roadmap. Copyright Florian Bernard. Published with permission. Click here to view.

The posterior limit of the frontal lobectomy protected the corticospinal tract. The second step was to open the frontal horn of the lateral ventricle using AR, anterior to the

TABLE 2. Patient characteristics and baseline information

	No. of Patients, n = 13 (%)
Female sex	8 (61.5)
Mean age, yrs	49.7
Surgical approach	
Frontal	7 (53.8)
Temporal	1 (7.7)
Occipital lateral	1 (7.7)
Parietal superior	2 (15.4)
Parietal inferior	1 (7.7)
Insular	1 (7.7)

FIG. 3. Frontal and temporal roadmaps. **A and B:** The frontal roadmap volume includes the superior and middle frontal gyri down to the frontal horn of the lateral ventricle and excludes the inferior frontal gyrus and the rectus gyrus. With this approach, the anterior and superior portions of the IFOF may be resected. The caudate nucleus and corticospinal tract are preserved. **C and D:** The temporal roadmap volume includes the superior to inferior temporal gyri, anterior to the vein of Labbé. After reaching the anterior and inferior portions of the temporal horn, the temporomesial part of the lobectomy can be performed. In so doing, the surgeon preserves the visual pathway, the IFOF, and the anterior commissure. The anterior portion of the ILF may be resected without clinical deficit. Yellow represents the anterior commissure; green, the superior longitudinal fasciculus (SLF) III; and red, the arcuate fasciculus. Dashed lines indicate the surgical roadmap.

caudate nucleus head. The lateral ventricles and the head of the caudate were defined as signature and target structures to be preserved, respectively. Navigation accuracy was checked using the overall ventricle cavity shape, the thalamoseptal vein, and the head and column of the fornix. Then the surgical corridor passed in front of the column of the fornix, at the level of the interventricular foramen and the anterior interhemispheric commissure. Anything anterior to this plane could theoretically be removed. Posterior to this plane and lateral to the ventricle were the body of the caudate nucleus and the anterior arm of the internal capsule, both of which were target structures to be preserved (Tables 1 and 3). The next intracerebral step was extension of the procedure to the medial limit of the frontal lobectomy. After opening the anterior part of the interhemispheric fissure, the pericallosal and callosomarginal vessels served as signature structures to assess and correct navigation accuracy. The pericallosal and callosomarginal arteries needed to be preserved since they participate in the vascularization of the central region. When frontal lobectomies are performed on the dominant hemisphere,

the inferior frontal gyrus (pars opercularis and pars triangularis) and the posterior middle frontal gyrus should be preserved.

Roadmap for AR-Assisted Temporal Lobe Surgery

After patient positioning, anatomical landmarks were visualized on the scalp. Sutures associated with the temporal squama were used as bone landmarks. The anterior aspect of the middle fossa served as a reference to define the posterior coronal plane fixed at 5.5 cm and 4.5 cm in the nondominant and dominant hemispheres, respectively. The optic radiations, optic tract, choroidal artery, temporal horn of the lateral ventricle, brainstem, and tumor were visualized as signature or target structures. The craniotomy was designed to allow optimal access to the tumor resection cavity. The durotomy should expose the sylvian fissure and allow the dissection of the superior, middle, and inferior temporal gyri.

The first step was to identify the posterior limit of the temporal lobectomy. The vein of Labbé is an excellent signature structure for recalibrating the AR and should be

TABLE 3. Surgical roadmaps proposed by the authors

Approach	Tracked Anatomical Structure	Roadmap	Tools to Extend Resection
Frontal	Precentral gyrus & motor supplemental areas, caudate nucleus (head), frontal horn of the lat ventricle, fornix (column), corpus callosum, pericallosal arteries	1. Posterior approach to the frontal horn, anterior to the caudate nucleus 2. Resection superior & anterior to the fornix 3. Interhemispheric approach 4. Callosotomy	Corticospinal tract neuromonitoring
Temporal	Sylvian fissure & posterior temporal limit (5.5 cm rt, 4.5 cm lt), MCA (M ₂ & M ₃ segment), temporal horn of the lat ventricle, optic tracts (Meyer's loop), temporal uncus, hippocampus (head, body, tail)	1. Posterior approach to the temporal horn (anterior, lat, or inferior) 2. Resection inferior to the middle fossa 3. Hippocampus & uncus resection if needed	Optic tract neuromonitoring or awake brain surgery
Superior parietal	Postcentral gyrus, arcuate fasciculus & IFOF, atrium of the lat ventricle, optic radiation	1. Superior approach to the atrium 2. Inferior approach above the supramarginal gyrus to the atrium roof 3. Posterior approach anterior to the parietooccipital sulcus	Corticospinal & optic tract neuromonitoring or awake brain surgery (visual field, language)
Occipital lateral	Transverse & superior longitudinal sinus, calcarine sulcus, atrium & occipital part of the lat ventricle, IFOF, optic radiation	1. Medial approach to the occipital part of the lat ventricle lat to the IFOF & to the optic radiation 2. Lat approach posterior to the angular gyrus; superior, middle, & inferior gyri (regarding the line linking the parieto-occipital superiorly & the preoccipital notch) to the atrium 3. Inferior approach to tentorium	Optic tract neuromonitoring or awake brain surgery (visual field, language)

MCA = middle cerebral artery.

Each approach can be tailored to individual patients. The AR-assisted route is based on classic anatomical landmarks for lobectomy.

preserved. Usually, the pia mater of the superior temporal gyrus was coagulated parallel to the sylvian fissure, maintaining 5 mm of distance to avoid inadvertent coagulation of the arteries. Then, we proceeded to the resection of the lateral neocortical block. AR projection of the temporal ventricle horn as a target structure facilitated the surgeon's orientation (Figs. 1–3; Video 1). Indeed, at the posterior border of the resection, the medial limit of this surgical step consisted of opening the lateral ventricle's temporal horn. The approach to the ventricle can be tailored using AR to avoid certain fiber tracts according to the oncological aim and the accepted degree of postoperative disability. Opening of the temporal horn should be done anteriorly, and the posterior part of the resection should be done using an inferolateral approach to the temporal horn to reduce the risk of visual field deficits (anterior Meyer's loop fibers are superolateral to the ventricle).

After the depth of the temporal horn was determined, the sylvian fissure orientation guided the progression of the dissection toward the temporal pole. The dissection can be extended inferiorly down to the floor of the middle fossa. The amygdala, displayed as a target or signature structure, is the structure that protrudes into the ventricle anteriorly to the choroidal point, and it may be resected. At the junction between the amygdala and hippocampal head, resection was continued medially below the choroidal fissure.

Roadmap for AR-Assisted Occipital Lateral Lobectomy

As is often the case with occipital lesions, a patient presented with preoperative hemianopia, aphasia, and alexia linked to a left temporoccipital glioblastoma. Important structures to preserve include the visual word form area of

the inferior longitudinal fasciculus (ILF), the optic radiations, and the language anatomical structures (the arcuate fasciculus and inferior frontooccipital fasciculus). Superficially and anteriorly, AR was used to localize the angular gyrus and the posterior part of the (superior, middle, and inferior) temporal gyri. Deeper in the dissection, the arcuate fasciculus and the inferior frontooccipital fasciculus (IFOF) defined the anterior boundaries (Figs. 4, 5A, and 5B; Video 1). As the IFOF and optic radiations surround the lateral wall of the occipital horn, the preferred surgical trajectory aimed at a superior entry to the occipital horn. The principal signature structures were individually identified, including superficial vascular structures and the lateral ventricle. Postoperatively, the patient did not present with any alexia or language disturbances, and the preexisting visual field impairment had improved.

Roadmap for AR-Assisted Superior Parietal Surgery

For the superior parietal lobule roadmap, the postcentral sulcus was the anterior limit, and the parietooccipital sulcus was the posterior limit. Limits were the falx medially and the inferior parietal lobule laterally. The main surgical step was to reach the atrium superiorly and/or medially to preserve the optic radiation and the IFOF. The principal signature structures were individually identified using superficial vascular structures, such as postcentral veins (Figs. 5C, 5D, and 6) and the lateral ventricle.

Discussion

In this case series, we describe the use of AR-assisted surgery to optimize periventricular structure preservation.

FIG. 4. Intraoperative AR view of the occipital lateral roadmap. Using AR, the surgeon is guided to the entry point inside the occipital ventricular horn (blue), avoiding optic radiation fibers (medially) and the inferior frontooccipital fibers (medially and anteriorly).

Four standardized roadmaps, using a set of AR signature and target structures, are outlined to help surgeons define and localize classic, “safe” lobectomies. By using signature structures, the surgeon can confirm the accuracy of the navigation despite brain shift and display target structures to be preserved or removed. Other advanced neurosurgical tools, such as fluorescence, neuromonitoring, or awake brain surgery, may help the surgeon perform safer resections.³⁶

AR-Assisted Roadmaps

In modern neurosurgery, lobar approaches could be considered unnecessarily aggressive.⁷ Nevertheless, the experience acquired thus far, using the techniques adapted to newly developed tools, allows for defining new standard surgical procedures on common ground. Implementing these principles in AR-assisted approaches can not only offer guidance to younger surgeons but also support the development of more refined standard approaches worldwide, as with flight plans in aviation.¹¹

Regarding the frontal roadmap, the target structures to preserve are the corticospinal tract, the caudate nucleus, the column of the fornix, the subcallosal gyrus, and the anterior perforating substance, while using superficial vessels, ventricular cavities, the pericallosal arteries, and the anterior cerebral and middle cerebral arteries as sig-

nature structures to verify and correct for brain shift or deformations.¹⁶ This should allow increasing accuracy and preservation of the corticospinal tract and associated motor function (posteriorly), the IFOF (which is lateral to the caudate nucleus) implicated in language in the dominant hemisphere and the attentional networks in the nondominant hemisphere, and finally, the limbic system involved in emotion and memory (caudate nucleus and fornix) (Fig. 3A and B; Table 1).^{24–26} Tracking these major structures may help to build a better representation of a “safe” frontal lobe surgical volume. Better surgical orientation, and possibly more accurate navigation in association with neuromonitoring or awake brain surgery, may further increase surgical safety by reducing unintentional lesions of the corticospinal tract and structures associated with language, attention distribution, and cognitive function.^{24,26}

For the temporal roadmap, the target structures to preserve are the roof of the temporal horn, the optic tract, the optic radiations, the anterior commissure, the IFOF,⁷ and the brainstem. The signature structures include the vein of Labbé, the middle cerebral artery, the choroidal artery, and the ventricular cavity (Fig. 3).^{27,28} Posteriorly, it may help preserve the arcuate fasciculus and the ventral parietal fasciculus (also known as the posterior indirect arcuate fasciculus).^{18,20,24,29} Preoperative identification of major structures is critical to help integrate the “safe” temporal

FIG. 5. Occipital lateral and superior parietal lobule roadmaps. **A and B:** The occipital roadmap is difficult to define without functional mapping or preoperative neurological deficit. The ventricles are blocked by major association fibers, such as optic radiations (visual field risk), the IFOF (visuospatial cognition and language), and the ILF (face recognition and the visual word form area). **C and D:** The superior parietal lobule roadmap reaches the upper part of the atrium. It includes the SLF I and II. Note that the inferior part of the SLF II resection may induce unilateral neglect in the right hemisphere. With this roadmap, the visual pathway and the IFOF that is involved in the dorsal language stream and visuospatial cognition are preserved. The vertical occipital fasciculus, posterior commissure, and tapetum fiber tracts are not represented. Ant = anterior; Sup = superior.

lobe surgical volume. Additional use of neuromonitoring or awake brain surgery may help preserve the visual field, language, and visuospatial cognition.³⁰

The occipital roadmap is the most difficult to define without functional mapping. As proper periventricular landmarks do not exist for occipital lobectomy, the occipital landmarks are limited by major fiber tracts that course around to the occipital horn (see Table 1 in GÜNGÖR and colleagues' study¹⁷). The lateral wall of the occipital horn includes major fiber tracts (from more superficial to deeper: vertical occipital fasciculus, IFOF, posterior commissure, central part of the optic radiation, and tapetum). The inferior wall includes the anterior part of the optic radiations. The medial superior wall is free of the optic radiations; nevertheless, visual fibers travel medially to join the calcarine sulcus, and thus, it is advised to approach the occipital horn from above.

Other roadmaps, such as the inferior parietal lobule, temporoparietal junction, and insular cortex can be defined using other anatomofunctional landmarks. The surgical corridor for the inferior parietal lobule is anteriorly limited by the sylvian fissure, parietal operculum, intraparietal sulcus of Janssen between the supramarginal and the angular gyrus, and by Heschl's gyrus.³¹ Medially (superi-

orly and inferiorly) and posteriorly to the posterior end of Heschl's gyrus courses the arcuate fasciculus.^{18,25,29} In addition to these cortical and fiber tract landmarks, interindividual variation of functional anatomy requires additional pre- and intraoperative functional tests. Concerning the temporoparietal junction, the main functional limits are anteriorly and superiorly, with the posterior aspect of the middle and inferior temporal, inferior part of the supramarginal, and angular gyri. The posterior landmarks are the same as those for the occipitolateral approach. Regarding the insula, the anatomical boundaries are mainly medial. Superiorly, the anterior internal capsule courses and the AR signature structures include the periinsular sulcus or the M₂ segment; posteriorly, the retrolenticular part of the internal capsule; and medially, the arcuate fasciculus lateral to the claustrum and the IFOF between the claustrum and the putamen. The potential medial extension depends on the degree of spread of the tumor in the medial direction. Putative target structures are the emergence of the gray and white substance of the basal ganglia and the anterior perforated substance. Signature structures include the limen insulae, the M₁ segment of the middle cerebral artery, and the most distal lenticulostriate artery. Knowledge of the white matter anatomy and the orientation of

FIG. 6. Superior parietal lobule roadmap. **A and B:** Three-dimensional reconstruction of the brain (A) and the roadmap (B). An upper approach to the ventricle (blue) was planned to avoid the postcentral gyrus (red), SLF II (pink), IFOF (purple), optic radiation (yellow), and postcentral vein (arrowheads). **C:** Intraoperative AR view showing the roadmap and the ventricle relationships.

fibers is critical to favor dissection along the fiber path to lessen fiber tract damage.

Based on these anatomical principles, more complex roadmaps could also be developed, with adjunct functional testing during these tailored approaches.

Perspectives and Limitations

One might argue that this article is mainly descriptive and does not assess any clinical or patient outcome. In the scientific steps to establish AR-assisted surgery, studies assessing feasibility,¹⁶ accuracy,²³ and safety are ongoing. This study aims to stimulate the debate regarding opportu-

nities to improve surgical standards by setting landmarks and procedures using AR-guided navigation.

Surface-matching patient registration³² or combined methods using surface-matching and paired-point registration³³ are considered to provide acceptable registration results, with an error of 4 mm. However, AR technology could intuitively be used to correct this mismatch through “intelligent” fusion between the injected image and the real structures using information from the field of the microscope. This correction could be performed at every stage of the surgery (i.e., using the skin surface, bone, sulci, veins, and arteries), but it requires the identification of unequivocal signature structures (Tables 1 and 3) at each

stage. Then, a comparison of the observed shape in the microscope with the calculated contours generated from neuronavigational data must be performed; the difference between these two data sets allows for the calculation of a convolution function that corrects for shifts and deformations.¹⁶ Moreover, in such a procedure, the neurosurgeon is empowered to intraoperatively perform multimodal checks that include their surgical experience, visual information, AR information, and other advanced tools.

Recent developments allow easy intraoperative navigation accuracy corrections using AR-based signature structures as references. Depending on the case, certain craniotomies could be large, and therefore brain shift could pose a major issue, which is why we recommend adopting a minimally invasive, tailored approach using AR. Smaller craniotomies and minimal dissection have been reported to have a positive impact on postoperative morbidity.^{34,35}

Conclusions

We describe and illustrate how classic concepts of intracerebral surgery can be transported to the era of AR-assisted surgery using periventricular anatomical landmarks. We believe that implementing these principles using AR-assisted approaches could offer guidance to younger surgeons and support the development of more refined standard approaches.

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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: Bernard, Bijlenga. Acquisition of data: Bernard, Bijlenga. Analysis and interpretation of data: Bernard, Bijlenga. Drafting the article: Bernard, Kiss-Bodolay, Bijlenga. Critically revising the article: Bernard, Haemmerli, Zegarek, Kiss-Bodolay, Bijlenga. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Bernard. Study supervision: Schaller, Bijlenga. English editing: Zegarek.

Supplemental Information

Videos

Video 1. <https://vimeo.com/558032600>.

Correspondence

Florian Bernard: Geneva University Hospitals, Geneva, Switzerland. bernardflorian.bf@gmail.com.