INNOVATIONS IN NEUROSURGERY

Abstract

The neurosurgical field has faced many challenges since its establishment in the past century. Conceptual, technical, and technological revolutions progressively reshaped the neurosurgical vision, pushing the previous boundaries to the next level. At the foundation of those revolutions, innovations were always the primum moves that induced a paradigm shift towards new frontiers. Operative microscopes, endoscopes, microneurosurgical instruments, neuronavigation systems, and intraoperative neuromonitoring represent just a few examples of the previous innovations that allow improving the neurosurgical healthcare. Nowadays, new technologies are emerging promising new revolutions in how neurosurgery vision is conceived. The upsurge of new visualization tools (e.g exoscope) equipped with extremely high magnification and augmented reality systems integration, confocal laser endomicroscopy to explore the surgical cavity at a cellular level, big data analysis through machine learning and artificial intelligence software, and a further and further hybridization with robotic neurosurgery will revolutionize the surgical practice beyond its present limits. In the following chapter, we will briefly present some of those innovations and discuss their implication in the neurosurgical practice.

Keywords: Neurosurgery; Innovations; Exoscope; Machine Learning; Virtual Reality; Artificial Intelligence

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I. INTRODUCTION

Neurosurgery is a fascinating and continuous-evolving discipline strictly connected to the technological innovation. Defined as “the introduction of a new technology that initiates a change in clinical practice”[1], innovations have represented the beating heart of this surgical branch, allowing to push it forward and overcome dogmatic concepts that could limit the improvement of the reference standard clinical practice. Professor Yaşargil and Professor Rhoton represent a remarkable example of innovators in this field, both sharing the desire to refine previous concepts and instruments, and changing for the better the neurosurgery legacy. Professor Yaşargil developed the modern concept of microneurosurgery with the introduction of the operative microscope and the refinement of microsurgical instruments such as aneurysm clips and brain retractors; Professor Rhoton, a pioneer of microneurosurgical anatomy, introduced new surgical techniques and developed innovative neurosurgical instruments (e.g. Rhotonmicrodissectors), transforming the way neuroanatomy is taught.

More recently, The introduction of visualization tools (operative microscope and endoscope), neuronavigation systems, intraoperative neuromonitoring, fluorophores intraoperative fluorescence imagingin oncologic surgery, endovascular devices, minimally invasive treatment modality (e.g. laser interstitial thermal therapy), etc[1,2]have determined a paradigm-shift in the therein concept of neurosurgery, allowing to treat pathologies lesionsconsidered until than then“inoperable”, minimize the surgical invasiveness and reduce surgical-related complications. In the next few years, many innovations are expected to emerge. The concept of machine learning (ML),Machine vision, Artificial intelligence (AI), and neural network based deep learning (DL) conceptsare gaining momentum in neurosurgery, promising to revolutionize the diagnostic and decision-making processes inside and outside the operative theater (OT) [3,4]. Moreover, technological advancements such as robotic neurosurgery [5,6] and virtual reality (VR) [7]will increasingly be an essential component of surgical procedures, providing safer, more efficient, and tailored procedure for every patient.

In the following paragraphs,we will discuss some emerging innovations and propose possible future scenarios regarding innovations in neurosurgery.

II. EXOSCOPE (IINTEGRATEDION WITH ARTIFICIAL INTELLIGENCEAI, VRVIRTUAL REALITY, MRI MRIAND LIDAR LIDARWITH NNAVIGATION) (H1)

The exoscope (EX) represent a new emerging visualization tool in the neurosurgical field.The introduction of the operative microscope (OM) in the 1950’s characterized one of the first technological revolutions in neurosurgery, pioneering the conception ofmicro-neurosurgeryestablished on its capability to provide magnification, stereoscopic vision, and lighting on the operative field [8]. Subsequently the endoscope (EN)had been developed to overcome some of the OM limitations, bringing a new perspective on the minimally-invasive approaches and establishing the angled view with dedicated optic systems.However, the need to implement a three-dimensional vision, improves the surgery-related ergonomics, and provides a fully digital imaging for robotic integration into the OT lead to the conceptualization of the EX [9,10].

Composed of a 3D, high-resolution (4K), digital camera placed at the end of a robotic arm with 7 or more degrees of freedom (DOF) connected to a digital screen,the EX stands outside the surgical field providing high magnification images at a greater distance through a longer focal length, allowing better ergonomics and reducing the cumbersome of the OM, which has to be all the time, “connected” to the surgeon [9,11].Furthermore, this new facility is equipped with a foot-switch pedal, introducing the possibility to get better movement controls of the camera without the need to interrupt the surgery for required progressive adjustments, and a digital camera, consenting to integrate multiple intraoperative fluorophores (e.g. indocyanine green .[ICG], 5-aminolevulinic acid [5-ALA], and sodium fluorescein [SF])[11,12,13,14] for an immersive surgical experience (Figure 1).

Regarding the clinical applications, the safety and feasibility of the use of EX in the surgical practice has been proved in numerous case series study, spanning from neurovascular to oncologicaland spinal surgery, showing non-inferiority outcomes compared to the OM [9,15,16].Moreover, also an educational role has been advocated for this platform, enhancing the visualisation of the surgical field for the OT staff, students,and procedure attenders [9].However, as few limitations are emerging as this equipment becomes more widespread, further possible implementations of this technology are worthy of discussion.

One of the drawbacks of this technology is represented bypotential conflict conditions between the camera holding arm and the visualisation screen; in fact, as not all the different type of EXsare equipped with an independent monitor, an overlapping of the robotic arm with the line of sight of the monitor could occur,limiting the surgeon’ view during some stages of the procedure. Similarly, dedicatedintraoperative filters for oncologic and neurovascular surgeries are only partially available in first-generation EXs, restraining their clinical usefulness in specific settings [15]. Finally, the absence of a dedicated endoscopic holder integrated into the EX represent a shortcoming as one hand of the surgeon or the assistant is required to held holdthe endoscope ENlimiting the surgical dexterity, especially in narrow surgical fields such as skull base or posterior fossa procedures, or requiring additional facilities, increasing the final cost to perform the surgery [17]. Nevertheless, some limitations could be easily overcome as the integration of the tumoral and vascular filters are nowadays accessible in almost all new-generation EXs (Figure 2), and separated widescreen could be introduced in the OT to maximise the surgeon field-of-view [9,11].Conversely, for the endoscopic holder, further technical improvements have to be done to face this demand. In the author’s experience some efforts are required at the beginning to familiarize with the EX with a steep learning curve; however, after several procedures, the EX use become effortless, with a better vision and ergonomics compared to the OM.

Apart from the current limitations, a further section should be reserved to envision the future scenarios for the fulfilment of the potential that this new visualisation system seems to offer. In the Authors’ vision, specific implementations should be pursued to meet the emerging needs of a surgery which is increasingly interlinked with technological advancements:

III. VIRTUAL AND AAUGMENTED RREALITY (H2)

The introduction of the VR and augmented reality (AR) into the OT could represent a potential revolution, reshaping neurosurgery as it is currently conceived [18].Magnetic resonance imaging (MRI) or computed tomography (CT)–based 3D model,based on segmentation of the lesion and the key anatomical structures, can be obtained with pre-operative software and superimposed to the surgical field, allowing the surgeon to have an enhanced and immersive vision during the entire procedure, from the surgical positioning to the removal of the lesion.In support of this vision, a growing number of publications are emerging regarding this topic, providing data about the feasibility and safety of the application of VR/AR–assistedneurosurgery [19,20,21,22]. These technologies, along with the opportunity to display on the same screen real-time anatomical images, diffusion tensor imaging (DTI), and qualitative images modalitiesy (e.g. 5-ALA and ICG) are paving the way for a new standard of care.

IV. MACHINE VISION (H2)

Machine Vision (MV) is another emerging innovation that is gaining interest in complex data analysis and the subsequent translation of that information into the clinical scenario. The use ofMV , based on AI and ML processes, could play a role in the future in the neurosurgical practice.In fact, ML algorithms seem to provide encouraging data about the viability to automatically recognise key anatomical landmarks in endoscopic transsphenoidal surgery [23,24], opening new perspective of this application for segmentation and intraoperative recognition of anatomical structures.This synergy between MV and the surgeon could have interesting implicationsespecially during complex surgical procedures in which the pathology has caused a complete distortion of the anatomical landmarks, posing challenges in the recognitionidentification and preservation of delicate and eloquent anatomical structures. Another neurosurgery-related application of MV should be focused on the implementation of the neuronavigation system. Actually, the neuronavigation devices relies on a magnetic or optic co-registration software between spatial coordinates, based on the patient' physical space acquired in the OT, and pre-operative imaging; the fusion of those data allows to match in an univocal way each point in the recordedthree-dimensional space with the corresponding anatomical location on the radiological images. However, the variation of the intracranial or spinal volumes during the surgical procedure, mainly due to loss of cerebrospinal fluid and/or tissue and gravitational effects, produce a distortion called "brain shift", invalidating the patient-image registration [25]. Despite several methods have been proposed to compensate brain shift, in the clinical practice the most frequent practise is based on the acquisition of new intraoperative imaging (e.g. intraoperative CT/MRI or ultrasound) [25,26]. Although those technologies are capable to provide good results in term of brain shit correction,are burdened by limitations such as being expensive, time-consuming, and/or operator dependent . We advocate as a possible solution the implementation of the neuronavigation system integrated to the EXwith compensatory mechanisms based on MV processes such as the laser imaging detection and ranging (LIDAR) technology. This device showed promising result in the near real-time correctionof brain deformation due to a continuous stream of data between the laser range scanner (LRS), thesurgical field, and the workstation with a dedicated deformation correction software [27,28,29]. In the near future, this implemented system will provide to the surgeon a real-time correction of the brain shift phenomenon, for an increasingly immersive and safe surgery.

V. REAL-TTIME CCELLULAR VVISUALIZATION (H2)

The development of confocal laser endomicroscopy (CLE)technology, based on a miniatured confocal microscope combined with fluorescent dye (SF), pioneered the opportunity to have a real-time intraoperative visualisation of the histopathologic appearance of the surgical field [30,31].The high-resolution cellular visualization allowed by this innovation provide the opportunity to make an intraoperativediagnosis , check for tumoral infiltration of the suspected border of the lesion, and adapt the surgical strategy accordingly to the pathological data [32]. In the future, the interaction of this technology with ML algorithm will offer at the surgeon the opportunity to check the tumor removal also inat a microscopic scale, analysing the histoarchitectural cellular patterns along the surgical cavity and providing qualitative data regarding the surgical resection.

VI. SSCOOP (MECHANICAL CUSA WITH PPIEZOELECTRIC CCRYSTALS) (H1)

The advent of the ultrasonic aspirator (UA) had represented a significant innovation into the neurosurgical practice. Through its capacity to be tissue-selective, removing the pathological tissue while preserving the adjacent structures by leveraging the physical principle of cavitation, this instrument has gradually taken hold in the neurosurgical field. The piezoelectric transducer integrated in the UA is able to convert electromagnetic energy into variable-range ultrasonic waves and mechanical vibrations that, delivered through the tip of the instruments, lead to a fragmentation of non-elastic tissues (tumor-like)and sparing of elastic tissues (brain and vessel-like).The other components of the UA, consisting of irrigation and suction devices, allow the cooling of the instrument and the removal of the debrided tissues. This technology initially applied in cranial procedures [33], have progressively found further applications in the clinical practice such as spinal [34] and endoscopic procedures [35,36]afterwards the introduction of technical innovations, including tip alterations for bone and fibrotic lesion excision [37] and fusion with intraoperative neuromonitoring devices [38].Furthermore, UA use has been associated with a significant blood loss and surgical time reduction compared with the traditional instrumentation [35].Albeit those advantages, some limitations including the cost could limit the spread of this essential technology, especially in low-middle income countries. In the attempt to overcome this limitation and provide a greater dissemination of this tool, we have designed a low-cost instrument with analogous proprieties to the UA. This technology utilises the same physical principle of the UA, generating ultrasonic waves from the piezoelectric crystals embodied within the base of a normal electric toothbrush, capable of generate frequencies between 1.6 and 4.8 MHz [39]. Along with dedicated tips of different shape and size this tool is showing encouraging results in terms of safety and efficacy profiles in the resection of intracranial tumors (unpublished data),acting as a low-cost and widely-available alternative to traditional UAs.Finally, as future direction, the next-generation neurosurgical instruments should pursue the utmost interchangeability of functions, incorporating multiple technologies (e.g.coblation, suction, irrigation, cavitation, intraoperative neurophysiological monitoring, etc.) that could be activated by the operator without having to constantly interrupt the surgical manoeuvre, shortening the surgical timing, and increasing the efficiency of the procedure.

VII. HEADREST WITH MMOTORIZED RRETRACTORS (H1)

Headrest devices, mainly represented by the horseshoe headrest and the Mayfield or Sugita skull clamp, play a pivotal role in neurosurgery, ranging from the positioning of the patient prior to the surgical procedure to ensuring the accuracy of non-frameless navigation systems and prevention of surgery-related complications [40,41]. Moreover, the headrest may serve as an anchoring support for the placement of brain retractor holders, frequently used in the skull base, oncologic, and aneurysm surgery. Nevertheless, although this method provides undeniable visualization advantages, it is burdened by not risible rates of parenchymal and vascular injuries (5-10%)associated with the focal pressure applied by the retraction system [42]. Several techniques have been proposed over the years to limit the impact of retractors in brain surgery, establishing the concept of retractorless surgery [43] to minimize the retractor-induced tissue damage. New innovations are emerging also in this setting to face this issue and refine the surgical practice. Brain spatulas equipped with pressure sensor capable of monitoring in real-time the pressure applied to the cranial structures during the surgical procedure [44], soft robotic retractors composed of ferromagnetic microparticles scattered in a soft polymer matrix, able to expand and contract through a pneumatic system according to the surgical need [45], and motorized retractors capable of to modify the applied pressure through an external regulation system,seems foreseeable technological innovations for the improvement of the actual practice, striving for more and more atraumatic surgical procedures.

VIII. ARM SSUPPORTING SSYSTEM (FFORTIS TTRIMANO BASED HHANDREST) (H1)

Arm supporting systemrepresents another basic but essential neurosurgical tool to accomplishmicroneurosurgicalprocedures stabilizing surgeon arms and reducing hand tremble [46], increasing the surgeon control in the performance of microscopic maneuver.Different types of arm-holding devices have been presented in the last decades, from the first fixed armrest to freely movable armrest integrated with robotic technologies, able to reduce surgical fatigue and offer a dynamic supportadapting to position changes required during complex surgical procedure [47,48].Nevertheless, despite those advantages, the robotic armrest deployment is actually limited to a few centers and focused mainly on research purposes, as some cost-effectiveness and cumbersome issues have been highlighted [47,48]. A feasible and effective solution can be reached through the customization ofanhydraulic arm commonly used in orthopedic surgery (e.g.TrimanoFortisTM) [49]. This compact and multi-planar armcan be easily secured to the operating table or dedicated chairs, offering an excellent handling for intra-operative adjustments of the arm supporting system and optimizing the surgical performance.

IX. LASER CCARRIERS FOR TTUMOR RRESECTION (H1)

Laser interstitial thermal therapy (LITT) has recently emerged as an alternative and minimally invasive method for the treatment of primary and metastatic brain tumors, spinal lesions, and drug-resistant epilepsy [50,51,52,53], especially in case of tumor located in deep-seated structures or patients with contraindications to open surgery [53].Relying on stereotactical principles, the operative technique, usually performed in a dedicated MRI suite, contemplates the identification of the entry-point, the trajectory, and target on the pre-operative imagingand the insertion of the laser needle probe under neuronagivation guidance thought a stereotactic bolt. Once the desired target has been reached and the benchmark temperature has been set, the ablation procedure is performed under dedicated MRI-thermometry sequences in order to avoid possible hyperthermia-related injuries [54].A further strength of LITT systemcan be sought in the opportunity to treat multiple contiguous and noncontiguous lesions, increasing the number of fibers, and the feasibility of perform a LITT retreatment [55,56]. However, although this promising data, several pit falls of this technology are restraining a broader application. New neurological deficits, catheter misplacement, and intracranial hemorrhage represents some of the complications related to the LITT [51,54,57]. The refinement of the laser technology, with the introduction of smaller and multiple, radially arranged termination tipsmay limit the need to deliver high temperatures, restricting the ablating effect only on the pathologic target and preserving the surrounding normal brain tissue.

X. TUBULAR RRETRACTOR SSYSTEM IN NNEUROSURGERY (H1)

Brain retractors represent amainstay during microsurgical procedures, providing an adequate and stable exposure of deep-seatedlocations and enhancing the surgeon visibility along narrow corridors required for performing complex oncological and vascular procedures. Brain spatulas have represented the prevailing instrument in the last century, but as this retraction system can cause significant parenchymal and vascular damage to the surrounding structures, mainly due to pressure-induced ischemia and their sharp edges [58,59], frameless stereotactic tubular retractors had progressively gained momentum in the neurosurgical community as a safe, effective, and minimally invasive technique to decrease the cortex and white matter fiber-tracts retractor-induced lesions [60,61].Recent meta-analysis confirmed the reduction of complication rates with the use of tubular systems compared to traditional brain retractors [62,63]. Nevertheless, MRI-findings showed as even with the tubular retractor system minorretraction-induced injuries are still detectable [64].Aviable opportunity optionto chase a further brain-invasiveness reduction could be found in the development of dynamic tubular retractor devices, exploiting pneumatic systems or smart materials (e.g. nanorobots) able to adapt their shapes according to time-to-time needs [45,65]. Those innovations will be proficient in the provision of a tailored surgical accessibility, creating a safe operative corridor and applying shearing forces in a dynamic manner to minimize the pressure-induced tissue damage.

XI. CATHETER BBASED TTEMPORARY CCLIP (H1)

Temporary occlusion of cerebral vessels is a routinely practice for the neurosurgeon performing vascular and complex skull base cases, finding its foremost application in aneurysm surgery. This manoeuvre, known as temporary clipping, is used with the aim to obtain a proximal and/or distal control, ensuring a safe aneurysmal dissection from the surrounding structures and preventing potential bleeding in case of intra-operative aneurysm rupture or aneurysm-remodelling procedures. However, those advantages are burdened by some drawbacks as as, with the reduction of cerebral perfusion; in fact , ischemic event could canoccurin response to the prolonged occlusion of the vessels [66]. Despite the safe occlusion time may vary according to the parent artery and collateral vessels, longer prolongedtime of occlusion have been recognised a risk factor for the development of cerebral infraction [67,68] and intraoperative neuromonitoring changes [69]. To reduce the incidence of ischemic events an intermittent temporary clipping technique has been proposed but the continuous application and removal of the clip can be troublesome if delicate anatomical structures such perforator vessels and cranial nerves are in a strict relationship with the temporary clip. An interesting innovation that could be introduced to obtain an intermitting clipping reducing the concerns related to the clip repositioning could be represented by a catheter based tool able to provide aremote-adjustable pressure-controlled system. Regulated by a hydraulic or pneumatic mechanism, this tool will offer the chance to release the pressure on the clip,ensuring an adequate perfusion pressure and cerebral oxygenation to the brain parenchyma during the surgical steps judged as “safe”, and arrest in real-time the bleeding in caseof aneurysm rupture.

Summary: In this chapter we presented some innovations that in the authors’ vision will be able to implement and reshape the current concept of neurosurgery. The need for a closer and closer hybridization between neurosurgery, emerging technologies, and artificial intelligence algorithms is mandatory and will characterize the next decades, pushing forward the actual boundaries of the healthcare as is nowadays conceived. Despite some limitations will have to be faced, the necessity of a new technological revolution with the introduction of new innovations to optimize the patient care and reduce the surgical-related invasiveness is beyond dispute. We hope that sharing those ideas and stressing those concepts we could have paved the path for a new neurosurgical era.

REFERENCES

[1] Marcus HJ, Hughes-Hallett A, Kwasnicki RM, Darzi A, Yang GZ, Nandi D. Technological innovation in neurosurgery: a quantitative study. J Neurosurg. 2015 Jul;123(1):174-81. doi: 10.3171/2014.12.JNS141422. Epub 2015 Feb 20. PMID: 25699414; PMCID: PMC4446106.
[2] Zaki MM, Cote DJ, Muskens IS, Smith TR, Broekman ML. Defining Innovation in Neurosurgery: Results from an International Survey. World Neurosurg. 2018 Jun;114:e1038-e1048. doi: 10.1016/j.wneu.2018.03.142. Epub 2018 Mar 29. PMID: 29604357.
[3] Raju B, Jumah F, Ashraf O, Narayan V, Gupta G, Sun H, Hilden P, Nanda A. Big data, machine learning, and artificial intelligence: a field guide for neurosurgeons. J Neurosurg. 2020 Oct 2:1-11. doi: 10.3171/2020.5.JNS201288. Epub ahead of print. PMID: 33007750.
[4] Panesar SS, Kliot M, Parrish R, Fernandez-Miranda J, Cagle Y, Britz GW. Promises and Perils of Artificial Intelligence in Neurosurgery. Neurosurgery. 2020 Jul 1;87(1):33-44. doi: 10.1093/neuros/nyz471. PMID: 31748800.
[5] Wagner CR, Phillips T, Roux S, Corrigan JP. Future Directions in Robotic Neurosurgery. OperNeurosurg (Hagerstown). 2021 Sep 15;21(4):173-180. doi: 10.1093/ons/opab135. PMID: 34051701.
[6] Ball T, González-Martínez J, Zemmar A, Sweid A, Chandra S, VanSickle D, Neimat JS, Jabbour P, Wu C. Robotic Applications in Cranial Neurosurgery: Current and Future. OperNeurosurg (Hagerstown). 2021 Nov 15;21(6):371-379. doi: 10.1093/ons/opab217. PMID: 34192764.
[7] Fiani B, De Stefano F, Kondilis A, Covarrubias C, Reier L, Sarhadi K. Virtual Reality in Neurosurgery: "Can You See It?"-A Review of the Current Applications and Future Potential. World Neurosurg. 2020 Sep;141:291-298. doi: 10.1016/j.wneu.2020.06.066. Epub 2020 Jun 17. PMID: 32561486.
[8] Uluç K, Kujoth GC, Başkaya MK. Operating microscopes: past, present, and future. Neurosurg Focus. 2009 Sep;27(3):E4. doi: 10.3171/2009.6.FOCUS09120. PMID: 19722819.
[9] Ricciardi L, Chaichana KL, Cardia A, Stifano V, Rossini Z, Olivi A, Sturiale CL. The exoscope in neurosurgery: an innovative "point of view". A systematic review of the technical, surgical and educational aspects. World Neurosurg. 2019 Jan 17:S1878-8750(19)30080-4. doi: 10.1016/j.wneu.2018.12.202. Epub ahead of print. PMID: 30660891.

[10] Rösler J, Georgiev S, Roethe AL, Chakkalakal D, Acker G, Dengler NF, Prinz V, Hecht N, Faust K, Schneider U, Bayerl S, Czabanka M, Misch M, Onken J, Vajkoczy P, Picht T. Clinical implementation of a 3D4K-exoscope (Orbeye) in microneurosurgery. Neurosurg Rev. 2022 Feb;45(1):627-635. doi: 10.1007/s10143-021-01577-3. Epub 2021 Jun 18. PMID: 34142267; PMCID: PMC8827320.

[11] Maurer S, Prinz V, Qasem LE, Lucia KE, Rösler J, Picht T, Konczalla J, Czabanka M. Evaluation of a Novel Three-Dimensional Robotic Digital Microscope (Aeos) in Neurosurgery. Cancers (Basel). 2021 Aug 25;13(17):4273. doi: 10.3390/cancers13174273. PMID: 34503083; PMCID: PMC8428371.

[12] Smithee W, Chakravarthi S, Epping A, Kassam M, Monroy-Sosa A, Thota A, Kura B, Rovin RA, Fukui MB, Kassam AB. Initial Experience with Exoscopic-Based Intraoperative Indocyanine Green Fluorescence Video Angiography in Cerebrovascular Surgery: A Preliminary Case Series Showing Feasibility, Safety, and Next-Generation Handheld Form-Factor. World Neurosurg. 2020 Jun;138:e82-e94. doi: 10.1016/j.wneu.2020.01.244. Epub 2020 Feb 8. PMID: 32045725.

[13] Muto J, Mine Y, Nakagawa Y, Joko M, Kagami H, Inaba M, Hasegawa M, Lee JYK, Hirose Y. Intraoperative real-time near-infrared optical imaging for the identification of metastatic brain tumors via microscope and exoscope. Neurosurg Focus. 2021 Jan;50(1):E11. doi: 10.3171/2020.10.FOCUS20767. PMID: 33386024.

[14] Schupper, A. J., Roa, J. A., &Hadjipanayis, C. G. (2022). Contemporary intraoperative visualization for GBM with use of exoscope, 5-ALA fluorescence-guided surgery and tractography. Neurosurgical Focus: Video, 6(1), V5.

[15] Amoo M, Henry J, Javadpour M. Beyond magnification and illumination: preliminary clinical experience with the 4K 3D ORBEYE™ exoscope and a literature review. Acta Neurochir (Wien). 2021 Aug;163(8):2107-2115. doi: 10.1007/s00701-021-04838-8. Epub 2021 Apr 2. PMID: 33797629.

[16] Vetrano IG, Acerbi F, Falco J, D'Ammando A, Devigili G, Nazzi V. High-Definition 4K 3D Exoscope (ORBEYETM) in Peripheral Nerve Sheath Tumor Surgery: A Preliminary, Explorative, Pilot Study. OperNeurosurg (Hagerstown). 2020 Sep 15;19(4):480-488. doi: 10.1093/ons/opaa090. PMID: 32357216.

[17] Yano S, Hiraoka F, Morita H, Kawano H, Kuwajima T, Yoshida SI, Hama Y, Tashiro N, Hamaguchi S, Aikawa H, Go Y, Kazekawa K. Usefulness of endoscope-assisted surgery under exoscopic view in skull base surgery: A technical note. Surg Neurol Int. 2022 Feb 11;13:30. doi: 10.25259/SNI_965_2021. PMID: 35242396; PMCID: PMC8888302.

[18] Gagandeep S, Tejasvi K, Nihal M, Shubham J, Anatoliy V, Vadim S, Prateek P, Sunil M. Editorial. Long-term solutions in neurosurgery using extended reality technologies. Neurosurg Focus. 2021 Aug;51(2):E2. doi: 10.3171/2021.5.FOCUS21235. PMID: 34333475.

[19] Mascitelli JR, Schlachter L, Chartrain AG, Oemke H, Gilligan J, Costa AB, Shrivastava RK, Bederson JB. Navigation-Linked Heads-Up Display in Intracranial Surgery: Early Experience. OperNeurosurg (Hagerstown). 2018 Aug 1;15(2):184-193. doi: 10.1093/ons/opx205. PMID: 29040677; PMCID: PMC6047456.

[20] Salgado-Lopez L, Oemke H, Feng R, et al. Intraoperative use of heads-up display in skull base surgery. Neurosurgical Focus: Video. 2022;6(1):V2-. doi:10.3171/2021.10.FOCVID21177

[21] Scherschinski L, McNeill IT, Schlachter L, Shuman WH, Oemke H, Yaeger KA, Bederson JB. Augmented reality-assisted microsurgical resection of brain arteriovenous malformations: illustrative case. J Neurosurg Case Lessons. 2022 Jun 20;3(25):CASE21135. doi: 10.3171/CASE21135. PMID: 35733837; PMCID: PMC9210269.

[22] Roethe AL, Rösler J, Misch M, Vajkoczy P, Picht T. Augmented reality visualization in brain lesions: a prospective randomized controlled evaluation of its potential and current limitations in navigated microneurosurgery. Acta Neurochir (Wien). 2022 Jan;164(1):3-14. doi: 10.1007/s00701-021-05045-1. Epub 2021 Dec 13. PMID: 34904183; PMCID: PMC8761141.

[23] Staartjes VE, Volokitin A, Regli L, Konukoglu E, Serra C. Machine Vision for Real-Time Intraoperative Anatomic Guidance: A Proof-of-Concept Study in Endoscopic Pituitary Surgery.

OperNeurosurg (Hagerstown). 2021 Sep 15;21(4):242-247. doi: 10.1093/ons/opab187. PMID: 34131753.

[24] Khan DZ, Luengo I, Barbarisi S, et al. Automated operative workflow analysis of endoscopic pituitary surgery using machine learning: development and preclinical evaluation (IDEAL stage 0). Journal of Neurosurgery. 2022;137(1):51-58. doi:10.3171/2021.6.JNS21923

[25] Gerard IJ, Kersten-Oertel M, Hall JA, Sirhan D, Collins DL. Brain Shift in Neuronavigation of Brain Tumors: An Updated Review of Intra-Operative Ultrasound Applications. Front Oncol. 2021 Feb 8;10:618837. doi: 10.3389/fonc.2020.618837. PMID: 33628733; PMCID: PMC7897668.

[26] Iversen DH, Wein W, Lindseth F, Unsgård G, Reinertsen I. Automatic Intraoperative Correction of Brain Shift for Accurate Neuronavigation. World Neurosurg. 2018 Dec;120:e1071-e1078. doi: 10.1016/j.wneu.2018.09.012. Epub 2018 Sep 11. PMID: 30213682.

[27] Sun K, Pheiffer TS, Simpson AL, Weis JA, Thompson RC, Miga MI. Near Real-Time Computer Assisted Surgery for Brain Shift Correction Using Biomechanical Models. IEEE J TranslEng Health Med. 2014 Apr 30;2:2500113. doi: 10.1109/JTEHM.2014.2327628. PMID: 25914864; PMCID: PMC4405800.

[28] Bayer S, Maier A, Ostermeier M, Fahrig R. Intraoperative Imaging Modalities and Compensation for Brain Shift in Tumor Resection Surgery. Int J Biomed Imaging. 2017;2017:6028645. doi: 10.1155/2017/6028645. Epub 2017 Jun 5. Erratum in: Int J Biomed Imaging. 2019 Oct 1;2019:9249016. PMID: 28676821; PMCID: PMC5476838.

[29] Zhang C,YuanD. “Wireless transmission-based brain shift compensation system.” The Journal of Engineering. 2019(14). doi:10.1049/joe.2018.9408

[30] Belykh E, Miller EJ, Carotenuto A, Patel AA, Cavallo C, Martirosyan NL, Healey DR, Byvaltsev VA, Scheck AC, Lawton MT, Eschbacher JM, Nakaji P, Preul MC. Progress in Confocal Laser Endomicroscopy for Neurosurgery and Technical Nuances for Brain Tumor Imaging With Fluorescein. Front Oncol. 2019 Jul 3;9:554. doi: 10.3389/fonc.2019.00554. PMID: 31334106; PMCID: PMC6616132.

[31] Acerbi F, Pollo B, De Laurentis C, Restelli F, Falco J, Vetrano IG, Broggi M, Schiariti M, Tramacere I, Ferroli P, DiMeco F. Ex Vivo Fluorescein-Assisted Confocal Laser Endomicroscopy (CONVIVO® System) in Patients With Glioblastoma: Results From a Prospective Study. Front Oncol. 2020 Dec 23;10:606574. doi: 10.3389/fonc.2020.606574. PMID: 33425764; PMCID: PMC7787149.

[32] Abramov I, Park MT, Gooldy TC, et al. Real-time intraoperative surgical telepathology using confocal laser endomicroscopy. Neurosurgical Focus. 2022;52(6):E9-. doi:10.3171/2022.3.FOCUS2250

[33] Henzi S, Krayenbühl N, Bozinov O, Regli L, Stienen MN. Ultrasonic aspiration in neurosurgery: comparative analysis of complications and outcome for three commonly used models. Acta Neurochir (Wien). 2019 Oct;161(10):2073-2082. doi: 10.1007/s00701-019-04021-0. Epub 2019 Aug 3. PMID: 31377957; PMCID: PMC6739453.

[34] Nakagawa H, Kim S, Mizuno J, Ohara Y, Ito K. Technical advantages of an ultrasonic bone curette in spinal surgery. Journal of Neurosurgery: Spine. 2005;2(4):431-435. doi:10.3171/spi.2005.2.4.0431

[35] Baddour HM, Lupa MD, Patel ZM. Comparing use of the Sonopet(®) ultrasonic bone aspirator to traditional instrumentation during the endoscopic transsphenoidal approach in pituitary tumor resection. Int Forum Allergy Rhinol. 2013 Jul;3(7):588-91. doi: 10.1002/alr.21143. Epub 2013 Jan 7. PMID: 23292661.

[36] Cinalli G, Imperato A, Mirone G, Di Martino G, Nicosia G, Ruggiero C, Aliberti F, Spennato P. Initial experience with endoscopic ultrasonic aspirator in purely neuroendoscopic removal of intraventricular tumors. J NeurosurgPediatr. 2017 Mar;19(3):325-332. doi: 10.3171/2016.10.PEDS16352. Epub 2017 Jan 13. PMID: 28084922.

[37] Klopfenstein JD, Spetzler RF. (2004). Ultrasonic Aspirator Tip Variations: Instrumentation Assessment. Available at: https://www.barrowneuro.org/for-physicians-researchers/education/grand-rounds-publications-media/barrow-quarterly/volume-20-no-3-

2004/ultrasonic-aspirator-tip-variations-instrumentation-assessment-2/. (Accessed: 04 August 2022).

[38] Shiban E, Krieg SM, Obermueller T, Wostrack M, Meyer B, Ringel F. Continuous subcortical motor evoked potential stimulation using the tip of an ultrasonic aspirator for the resection of motor eloquent lesions. J Neurosurg. 2015 Aug;123(2):301-6. doi: 10.3171/2014.11.JNS141555. Epub 2015 May 15. PMID: 25978712.

[39] Takenouchi A, Otani E, Satoho Y, Kakegawa Y, Arai H, Matsukubo T. Comparison of the effects of ultrasound toothbrushes with different frequencies on oral hygiene: A randomized-controlled clinical trial. Int J Dent Hyg. 2021 Nov;19(4):376-381. doi: 10.1111/idh.12496. Epub 2021 Apr 13. PMID: 33763982.

[40] Beuriat PA, Jacquesson T, Jouanneau E, Berhouma M. Headholders' - complications in neurosurgery: A review of the literature and recommendations for its use. Neurochirurgie. 2016 Dec;62(6):289-294. doi: 10.1016/j.neuchi.2016.09.005. Epub 2016 Nov 17. PMID: 27865516.

[41] Thijs D, Menovsky T. The Mayfield Skull Clamp: A Literature Review of Its Complications and Technical Nuances for Application. World Neurosurg. 2021 Jul;151:102-109. doi: 10.1016/j.wneu.2021.04.081. Epub 2021 Apr 30. PMID: 33940273.

[42] Andrews RJ, Bringas JR. A review of brain retraction and recommendations for minimizing intraoperative brain injury. Neurosurgery. 1993 Dec;33(6):1052-63; discussion 1063-4. doi: 10.1227/00006123-199312000-00014. PMID: 8133991.

[43] Spetzler RF, Sanai N. The quiet revolution: retractorless surgery for complex vascular and skull base lesions. J Neurosurg. 2012 Feb;116(2):291-300. doi: 10.3171/2011.8.JNS101896. Epub 2011 Oct 7. PMID: 21981642.

[44] R.S. Karmakar, J.C. Wang, Y.T. Huang, et al. Real-time intraoperative pressure monitoring to avoid surgically induced localized brain injury using a miniaturized piezoresistive pressure sensor. ACS Omega, 5 (45) (2020), pp. 29342-29350

[45] Amadeo T, Van Lewen D, Janke T, Ranzani T, Devaiah A, Upadhyay U, Russo S. Soft Robotic Deployable Origami Actuators for Neurosurgical Brain Retraction. Front Robot AI. 2022 Jan 14;8:731010. doi: 10.3389/frobt.2021.731010. PMID: 35096979; PMCID: PMC8795889.

[46] Hara Y, Goto T, Okamoto J, Okuda H, Iseki H, Hongo K. An armrest is effective for reducing hand tremble in neurosurgeons. Neurol Med Chir (Tokyo). 2015;55(4):311-6. doi: 10.2176/nmc.oa.2014-0384. Epub 2015 Mar 23. PMID: 25797774; PMCID: PMC4628178.

[47] Ohta T, Kuroiwa T. Freely movable armrest for microneurosurgery: technical note. Neurosurgery. 2000 May;46(5):1259-61. doi: 10.1097/00006123-200005000-00049. PMID: 10807263.

[48] Goto T, Hongo K, Ogiwara T, Nagm A, Okamoto J, Muragaki Y, Lawton M, McDermott M, Berger M. Intelligent Surgeon's Arm Supporting System iArmS in Microscopic Neurosurgery Utilizing Robotic Technology. World Neurosurg. 2018 Nov;119:e661-e665. doi: 10.1016/j.wneu.2018.07.237. Epub 2018 Aug 6. PMID: 30092468.

[49] Gentile M et al. One-step distraction technique using TrimanoFortisTM arm in ankle arthroscopy. Foot & Ankle Surgery: Techniques, Reports & Cases. 2022, Volume 2, Issue 1, 100111

[50] Thomas JG, Rao G, Kew Y, Prabhu SS. Laser interstitial thermal therapy for newly diagnosed and recurrent glioblastoma. Neurosurg Focus. 2016 Oct;41(4):E12. doi: 10.3171/2016.7.FOCUS16234. PMID: 27690657.

[51] Diaz R, Ivan ME, Hanft S, Vanni S, Manzano G, Jagid J, Komotar RJ. Laser Interstitial Thermal Therapy: Lighting the Way to a New Treatment Option in Neurosurgery. Neurosurgery. 2016 Dec;79 Suppl 1:S3-S7. doi: 10.1227/NEU.0000000000001435. PMID: 27861320.

[52] Shah AH, Semonche A, Eichberg DG, Borowy V, Luther E, Sarkiss CA, Morell A, Mahavadi AK, Ivan ME, Komotar RJ. The Role of Laser Interstitial Thermal Therapy in Surgical Neuro-Oncology: Series of 100 Consecutive Patients. Neurosurgery. 2020 Aug 1;87(2):266-275. doi: 10.1093/neuros/nyz424. PMID: 31742351.

[53] Wu C, Schwalb JM, Rosenow JM, McKhann GM 2nd, Neimat JS; American Society for Stereotactic and Functional Neurosurgeons. The American Society for Stereotactic and

Functional Neurosurgery Position Statement on Laser Interstitial Thermal Therapy for the Treatment of Drug-Resistant Epilepsy. Neurosurgery. 2022 Feb 1;90(2):155-160. doi: 10.1227/NEU.0000000000001799. PMID: 34995216.

[54] Holste KG, Orringer DA. Laser interstitial thermal therapy. Neurooncol Adv. 2019 Dec 16;2(1):vdz035. doi: 10.1093/noajnl/vdz035. PMID: 32793888; PMCID: PMC7415254.

[55] O'Connor KP, Palejwala AH, Milton CK, Lu VM, Glenn CA, Sughrue ME, Conner AK. Laser Interstitial Thermal Therapy Case Series: Choosing the Correct Number of Fibers Depending on Lesion Size. OperNeurosurg (Hagerstown). 2020 Dec 15;20(1):18-23. doi: 10.1093/ons/opaa264. PMID: 32860413.

[56] Eichberg DG, Menaker SA, Jermakowicz WJ, Shah AH, Luther EM, Jamshidi AM, Semonche AM, Di L, Komotar RJ, Ivan ME. Multiple Iterations of Magnetic Resonance-Guided Laser Interstitial Thermal Ablation of Brain Metastases: Single Surgeon's Experience and Review of the Literature. OperNeurosurg (Hagerstown). 2020 Aug 1;19(2):195-204. doi: 10.1093/ons/opz375. PMID: 31828344.

[57] Pruitt R, Gamble A, Black K, Schulder M, Mehta AD. Complication avoidance in laser interstitial thermal therapy: lessons learned. J Neurosurg. 2017 Apr;126(4):1238-1245. doi: 10.3171/2016.3.JNS152147. Epub 2016 Jun 3. PMID: 27257839.

[58] Zhong J, Dujovny M, Perlin AR, Perez-Arjona E, Park HK, Diaz FG. Brain retraction injury. Neurol Res. 2003 Dec;25(8):831-8. doi: 10.1179/016164103771953925. PMID: 14669526.

[59] Dujovny M, Ibe O, Perlin A, Ryder T. Brain retractor systems. Neurol Res. 2010 Sep;32(7):675-83. doi: 10.1179/016164110X12644252260439. Epub 2010 Apr 30. PMID: 20433778.

[60] Kelly PJ, Goerss SJ, Kall BA. The stereotaxic retractor in computer-assisted stereotaxic microsurgery. Technical note. J Neurosurg. 1988 Aug;69(2):301-6. doi: 10.3171/jns.1988.69.2.0301. PMID: 3292721.

[61] Greenfield JP, Cobb WS, Tsouris AJ, Schwartz TH. Stereotactic minimally invasive tubular retractor system for deep brain lesions. Neurosurgery. 2008 Oct;63(4 Suppl 2):334-9; discussion 339-40. doi: 10.1227/01.neu.0000334741.61745.72. PMID: 18981840.

[62] Marenco-Hillembrand L, Prevatt C, Suarez-Meade P, Ruiz-Garcia H, Quinones-Hinojosa A, Chaichana KL. Minimally Invasive Surgical Outcomes for Deep-Seated Brain Lesions Treated with Different Tubular Retraction Systems: A Systematic Review and Meta-Analysis. World Neurosurg. 2020 Nov;143:537-545.e3. doi: 10.1016/j.wneu.2020.07.115. Epub 2020 Jul 23. PMID: 32712409.

[63] Echeverry N, Mansour S, MacKinnon G, Jaraki J, Shapiro S, Snelling B. Intracranial Tubular Retractor Systems: A Comparison and Review of the Literature of the BrainPath, Vycor, and METRx Tubular Retractors in the Management of Deep Brain Lesions. World Neurosurg. 2020 Nov;143:134-146. doi: 10.1016/j.wneu.2020.07.131. Epub 2020 Jul 24. PMID: 32717353.

[64] Bander ED, Jones SH, Kovanlikaya I, Schwartz TH. Utility of tubular retractors to minimize surgical brain injury in the removal of deep intraparenchymal lesions: a quantitative analysis of FLAIR hyperintensity and apparent diffusion coefficient maps. J Neurosurg. 2016 Apr;124(4):1053-60. doi: 10.3171/2015.4.JNS142576. Epub 2015 Oct 2. PMID: 26430838.

[65] Rus, D., Tolley, M.T. Design, fabrication and control of origami robots. Nat Rev Mater 3, 101–112 (2018). https://doi.org/10.1038/s41578-018-0009-8

[66] Woertgen C, Rothoerl RD, Albert R, Schebesch KM, Ullrich OW. Effects of temporary clipping during aneurysm surgery. Neurol Res. 2008;30:542–6.

[67] Samson D, Batjer HH, Bowman G, et al. A clinical study of the parameters and effects of temporary arterial occlusion in the management of intracranial aneurysms. Neurosurgery 1994; 34(1):22–28, discussion 28–29

[68] Kett-White R, Hutchinson PJ, Al-Rawi PG, et al. Cerebral oxygen and microdialysis monitoring during aneurysm surgery: effectsof blood pressure, cerebrospinal fluid drainage, and temporary clipping on infarction. J Neurosurg 2002;96(6):1013–1019

[69] Staarmann B, O'Neal K, Magner M, Zuccarello M.Sensitivity and Specificity of Intraoperative Neuromonitoring for Identifying Safety and Duration of Temporary Aneurysm Clipping Based

on Vascular Territory, a Multimodal Strategy.World Neurosurg. (2017) 100:522-530. http://dx.doi.org/10.1016/j.wneu.2017.01.009

FIGURE LEGENDS

Figure 1: Operating theatre setting and surgical view of the exoscope during oncological surgery. The exoscope camera lies above the surgeon working space, allowing a high degree of freedom of movements for the surgeon and the surgical instruments, and a free field of view to the surgeon, second surgeon, and operating theatre staff.

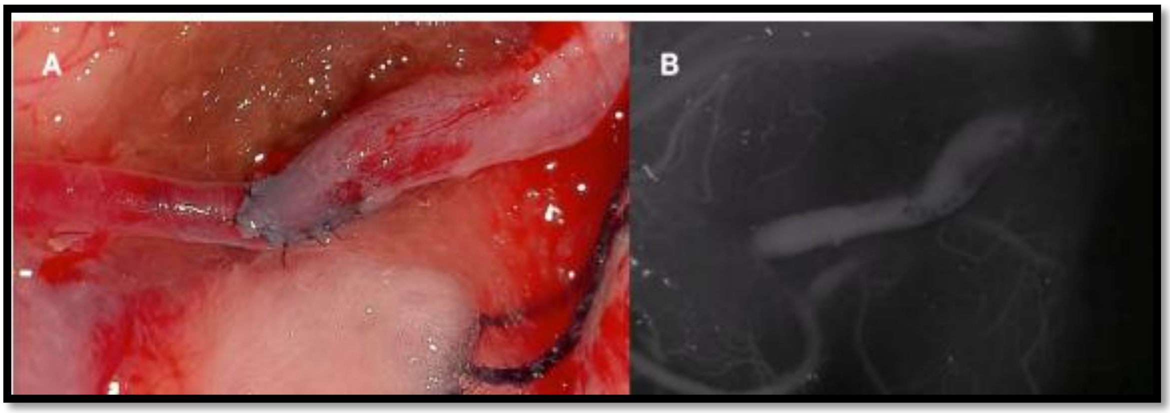

Figure 2: Intraoperativeexoscope high-magnification image showing the final stage of a superficial temporal artery – middle cerebral artery revascularization procedure (A) and the intraoperative indocyanine green video-angiography confirming the patency of the bypass (B).