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Intraoperative Imaging for High-Grade Glioma Surgery

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Intraoperative imaging

Intraoperative imaging, by acquiring and displaying timely information during surgery, provides a beneficial adjunct to glioma surgery. Gliomas can be difficult to differentiate from surrounding tissue making intraoperative estimates of residual tumor inaccurate. During surgical resection, brain shift of as much as 1 cm can occur after craniotomy and dural opening [1] due to CSF egress, diminished mass effect, osmotic diuresis, edema, lesion resection, or intraoperative pneumocephalus [2,3] These changes render preoperatively acquired images increasingly inaccurate as the surgery proceeds, limiting their usefulness in guiding intraoperative decision-making.

Intraoperative imaging allows visualization of brain shift and other changes which have occurred during tumor resection providing an updated set of images to guide additional tumor resection. The opportunity to perform additional resection reduces the need for return to OR, as residual tumor can be taken after the intraoperative scan and before closure [4]. Intraoperative imaging can also identify intraoperative complications such as hematoma so that these can be promptly managed while the patient is still in OR [2,4]. Through real time monitoring, intraoperative imaging has led to the development of novel interventions for gliomas including laser interstitial thermal therapy (LITT) and focused ultrasound blood brain barrier disruption (FUS BBBD).

While beneficial, intraoperative imaging and intraoperative MRI (iMRI) in particular also presents several clinical challenges. Between patient set up, scanning time, moving the MRI into and out of the operating room, instrument counts, and safety protocol procedures, iMRI can add over 2 hours to craniotomy [2]. Solutions to some of these inherent problems have been mitigated by establishing iMRI workflows and newer methods that shorten scanning

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times[2]. As newer technology becomes available such as 5-ALA[5] further studies are needed to establish the relative benefit costs of different intraoperative adjuncts.

Intraoperative Ultrasound (iUS)

The first report of iUS for brain tumors was by Ballantine et al. in 1950.[6] Original ultrasound techniques were first developed using 2D B-mode. This technology is based on pulsed acoustic waves that are reflected off the tissue of interest and detected at transducers to display their properties based on time and scattering. Most neurosurgical transducers operate within 1-25MHz and provide up to 10cm of depth penetration. A basic principle is that the higher the frequency, the better the resolution closer to the probe, however, higher frequencies have less penetration and hence less ability to image deeper structures (ex. 25MHz can provide maximum resolutions only a few centimeters from the emitting source). [7] Most often, the transducer type is determined by tumor size, craniotomy, anatomy of interest, and surgeon preference. iUS has significant advantages in that it has a lower cost of purchase and upkeep, takes up less OR space, is less disruptive to workflow, and may be available in settings in which intra-operative MR imaging is not available.[8]

Integration with Neuronavigation and Brain Shift

iUS has been an effective tool in maximizing resection of brain tumors [9–11] (Figure 1). Advances in technology have revitalized the use of iUS. Most US systems used in neurosurgical operating rooms use 2D B-mode ultrasound. One method of reconstructing a 3D image is to acquire a “sweep” of 2D images while tracking the probe with neuronavigation and rebuilding these into a 3-D dataset. This technique has provided powerful volumetric data that is typically collected by freehand sweeps, mechanical sweeps or a phased array transducer. [12] 3D ultrasound data can then be integrated and fused with pre-operative MRI scans for neuronavigaton [13–17]. Research groups have developed 3D US/MRI fusion-based neuronavigation and this approach has been commercialized recently.

Because intraoperative ultrasound offers real-time imaging, it can help by giving updated information regarding brain shift. There are a variety of techniques which have been applied to compensate for brain shift including rigid registration using hyperechoic structures [18], automated non-rigid registration [19–21], a “pseudo-US” technique [22], and vessel registration [23]. iUS is often compared to iMRI as both can provide updated imaging in the operating room. There are no randomized controlled trials, comparing iUS to iMRI, but there are mixed reviews showing less sensitivity in detecting small residual tumor volumes. [10,11,24,25].

Artifacts in intraoperative US

Although iUS usefulness improves with surgeon experience, there are conditions present during surgery such as blood products that can make interpretation variable and challenging. For instance, sound waves transmit through air at 330 m/s, saline at 1,480m/s, and brain tissue around 1,550 m/s. [26] This can produce errors in location of approximately 1.6mm, 10cm from the transducer. A clinically significant problem is that there is an artifactual hyperechoic signal due to changes in impedance at the margin of the fluid filled resection cavity and the surrounding parenchyma which makes interpretation of the images

particularly challenging in the area of greatest clinical concern. Recently, a promising acoustic coupling fluid has been developed to reduce this artifact, and is currently in phase 1 clinical studies [27].

Advanced iUS Modalities

There are a number of advanced ultrasound modalities currently in development. One promising well-studied technique, [28] is contrast enhanced ultrasound (CEUS). CEUS utilizes a microbubble based contrast, similar to that used in echocardiograhpy, which can outline gliomas, differentiate between tumor/edematous brain, provide grading information, show dynamic arterial/venous phases of the lesion, and be integrated to navigation systems as described above [29,30]. A recent review from our group, highlights the current state of the art. [31]

Intraoperative MRI (iMRI)

Intraoperative MRI (iMRI) in neurosurgery started at Brigham & Women's Hospital (BWH) in Boston, MA in 1994 (Figure 2) [2,32,33]. Between 1995 and 2007, over 1,000 craniotomies using iMRI were completed [4]. General Electric working closely with BWH in the early 1990's developed an open-configuration iMRI consisting of two vertically oriented superconducting magnets with separate communicating cryocoolers in a "double-donut" conformation [3,4]. The General Electric Signa System 0.5-T field machine allowed for the patient's head to be placed in the vertical gap between the coils, as close as possible to the magnet isocenter [3], minimizing spatial distortion and signal loss [34] while allowing for access to the patient by the surgeon and assistants. The system had the option of docking the operating table into the magnet sideways or lengthwise, depending on what configuration would maximize patient access [3]. The patient was fixed, and the MRI was also fixed; one did not need to move either to acquire iMRI. The main disadvantages of this early system were low field strength, which limited image resolution and the need for all surgical instruments and personnel to be MRI compatible[3].

In later iMRI systems, the MRI was fixed, but the patient had to be rotated into the MRI machine, which was placed at a 160 degree angle to the operating room table [35,36]. Other open-configuration iMRIs included the Siemens systems, including one with a table that could rotate into and out of a 1.5-T closed-bore magnet, and the Medtronic PoleStar system (Medtronic, Minneapolis, MN) [3]. The advantage of these systems was that minimal modifications to OR suites had to be made, unlike the original iMRI. The major disadvantage was again the relatively low field strength [32]

A significant development in iMRIs was the modification of diagnostic closed-configuration MRI scanners for intraoperative use. One system (IMRIS, Deerfield Imaging, Minnetonka, MN) is a rail-mounted system which moves the MRI instrument to the patient allowing for minimal patient movement [37,38]. Launched commercially in 2005 and first launched in Europe in 2010 [35], over 60 such systems have been installed worldwide to date [32]. A major advantage of iMRI with machines in or adjacent to ORs are that the patient does not need to be moved; therefore, IV lines, catheters, and endotracheal tubes are at less risk of dislodging [35].

To reduce scanning time, which prolongs overall surgical time, iMRI sequences can be tailored to particular types of tumors or lesions [2]. There is no universal iMRI protocol; rather, image sequences are obtained and reformatted into imaging planes and- if further resection is required-merged with stereotactic surgical navigation systems [34]. The standard sequences obtained during iMRI for glioma resections may include T1 (gadolinium enhanced or non-enhanced) T2, and fluid attenuated inversion recovery (FLAIR) as well as diffusion images [39].

Glioblastoma (GBM) and Extent of Resection

Maximal safe surgical resection of GBM is a key part of treatment. There are numerous studies showing a survival benefit with gross total resection of enhancing tumor [40–42]. iMRI can play a significant role in aiding the surgeon during the resection of GBMs including identifying incomplete resections (Figure 3) and updating the neuronavigation dataset. In a prospective randomized control study, Senft et al. showed that iMRI had more complete resections of the enhancing tumor than controls (96%) and a longer progression-free survival (226 days vs 98 days).[43] Another study identified 47% of patients who underwent additional resection because of residual disease identified on the intraoperative scan. [44] Napolitano et al. also showed in a non-randomized study that patients who underwent iMRI had a 17% improved quality of resection with 9% more gross total resection (GTR) without additional morbidity. iMRI may have an increasingly important role in the future as there is increasing emphasis on maximizing the extent of resection for particular molecular subtypes of GBMs [45,46].

iMRI-guided biopsies

iMRI-guided frameless stereotactic brain biopsy can confirm intraoperatively that the biopsy needle has reached its target location and converts a blind procedure into a visualized procedure with high histologic yield [47,48]. A prospective analysis (June 2009 to April 2011) showed that frameless stereotactic iMRI-guided tumor biopsy increased diagnostic effectiveness and safety and decreased cost [49]. Several systems for iMRI-guided biopsies currently exist. Neurogate (Daum GmbH, Germany) is an MR-compatible device for stereotactic biopsy of lesions [50]). A study of 28 patients between 1997 and 2000 with intracranial metastatic tumors or gliomas who underwent biopsy with Neurogate established stereotaxy in the open MRI as safe and accurate for intracranial biopsies [50]). Other available MRI-compatible biopsy systems include the Magnetic VisiOn (Magnetic VisiOn GmbH, Switzerland), the Heidelberger Interventions-Trajektor (Pilling Weck Chirurgische Produkte GmbH, Karlstein, Germany) and the Navigus trajectory guide (Image-Guided Neurologics, Inc., Melbourne, FL, USA) [50].

The Clearpoint Smartframe system (MRIInterventions, California, USA) is an MRI-compatible stereotactic tripod system originally developed for MRI-guided placement of deep brain stimulating electrode which can also be used for intracranial biopsies. The system consists of three circular fiducials and a cannula filled with gadolinium contrast [51]. It is typically mounted on the scalp through screws that pierce skin and penetrate the outer cranium table, or the frame can be mounted directly on the skull [52]. It provides submillimeter accuracy for stereotaxy [51]. Another option is Hall and Truwit's "prospective

stereotaxis" system which uses iMRI to target the lesion, monitor needle advancement, and track progress in real time at one to three images per second, and the needle can be advanced manually or via remote control [39,53,54]

Laser Interstitial Thermal Therapy (LITT)

The advent of MR thermometry allowed the controlled delivery of laser energy to the brain with near real time monitoring of heating. Thermal therapy emerged from an observation in 1891 that an inoperable sarcoma went into remission after a patient had a febrile strep infection [5556]. Treatment of cancer by thermal methods was bypassed in favor of radiation and chemotherapy until its resurgence in 1967, when Cavaliere et al. [57] proposed that cancer cells may be preferentially vulnerable to heat [56,57]. LITT was first used to ablate treatment-resistant focal metastatic intracranial tumors, and was then approved by the FDA for use of soft tissue ablation in neurosurgery (Figures 4a **and** 4b) [58,59]. Its use was later expanded to glioma surgery.

In a first clinical study of LITT in gliomas, median survival of 16 patients with supratentorial GBM who underwent LITT after first relapse increased from 9.4 to 11.2 months (vs. a natural history of survival <5 months or after temozolomide chemotherapy 5.4-7.1 months) [60]. LITT has been used to ablate newly diagnosed and recurrent GBMs. In a study of 8 patients with newly diagnosed and 13 patients with recurrent GBMs, LITT extended median survival from 2 to 8 months in newly diagnosed GBM; medial survival of patients with recurrent GBMs who underwent LITT was 7 months, suggesting LITT may be an effective salvage therapy [61]. LITT can also be used in cases of radiographic progression, especially when patients have few other salvage treatment options [62].

MR-guided LITT is a major advancement because it allows for monitoring of ablation in real time with MRI [63]. Without MRI guidance, LITT harbored an unacceptably high risk of thermal damage to the surrounding healthy brain [63]. The Visualase System by Medtronic is an MRI-guided laser ablation system used in the US since 2007. It gained CE approval in March 2018 [64,65]. The Neuroblate System by Monteris is currently the only robotic LITT system [66]. iMRI-guided LITT may be a safer alternative to patients in whom GBM is not accessible by surgery or in patients who are not surgical candidates due to medical comorbidities or other risks [67].

Intraoperative computed tomography (iCT)

iCT for glioma surgery was first described in the 1980s. [68]. The initial limitations were image quality and hardware artifact [69]. Current systems available include a multidetector CT which provides high resolution images of the soft tissue, or the cone-beam CT which provides better bony resolution with decreased cost and radiation exposure [70]. Although the imaging quality when compared to iMRI of intra-axial malignant tumors is poor, there is a significant advantage in terms of acquisition time, cost, maintenance, workflow and avoidance of room logistics such as magnetic shielding.

Because iCT offers the ability to image with the patient's head fixed in pins, it can be used to update neuronavigation, accommodate for brain shift, and obtain vascular imaging. [71].

This has also paved the way for automated registration techniques using a low-dose CT scan to reduce mean target registration errors to under 1mm. [72] One study showed the workflow interruption to obtaining an intraoperative scan is around 10-15 minutes with one of their 7 glioma patients needing further resection after the intraoperative scan. [69]

Conclusion

Intraoperative imaging is a useful adjunct to achieving a maximally safe resection during high-grade glioma surgery. There are a variety of modalities available including iMRI, iUS, iCT all of which aim to give the surgeon more information, address brain shift, identify residual tumor, and increase the extent of surgical resection.

References

1. Bernadette Henrichs., Walsh Robert P. Intraoperative MRI for neurosurgical and general surgical interventions. Curr Opin Anaesthesiol 2014;27(4):448–52. [PubMed: 24848271]
2. Thomas Ginat Daniel, Brooke Swearingen, William Curry., et al. 3 Tesla intraoperative MRI for brain tumor surgery. J Magn Reson Imaging 2014;39(6): 1357–65. [PubMed: 24921066]
3. Mislow John M. K., Golby Alexandra J., Black Peter M. Origins of intraoperative MRI. Magn Reson Imaging Clin N Am 2010;18(1):1–10. [PubMed: 19962089]
4. Peter Black., Jolesz Ferenc A., Khalid Medani. From vision to reality: the origins of intraoperative MR imaging. Acta Neurochir Supp1 2011;109:3–7.
5. Jenkinson Michael D., Giuseppe Barone Damiano, Hart Michael G., et al. Intraoperative imaging technology to maximise extent of resection for glioma. Cochrane Database of Systematic Reviews 2017 Doi: 10.1002/14651858.cd012788.
6. Ballantine HT Jr., Bolt RH, Hueter TF, et al. On the detection of intracranial pathology by ultrasound. Science 1950;112(2914):525–8. [PubMed: 14787454]
7. Serra C, Stauffer A, Actor B, et al. Intraoperative high frequency ultrasound in intracerebral high-grade tumors. Ultraschall Med 2012;33(7):E306–12. [PubMed: 23129521]
8. Aliasgar Moiyadi., Prakash Shetty. Objective assessment of utility of intraoperative ultrasound in resection of central nervous system tumors: A cost-effective tool for intraoperative navigation in neurosurgery. J Neurosci Rural Pract 2011;2(1):4–11. [PubMed: 21716843]
9. Syed Mahboob., Rachael McPhillips., Zhen Qiu., et al. Intraoperative Ultrasound-Guided Resection of Gliomas: A Meta-Analysis and Review of the Literature. World Neurosurg 2016;92:255–63. [PubMed: 27178235]
10. Ravn Munkvold Bodil Karoline., Store Jakola Asgeir., Ingerid Reinertsen., et al. The Diagnostic Properties of Intraoperative Ultrasound in Glioma Surgery and Factors Associated with Gross Total Tumor Resection. World Neurosurg 2018;115:e129–36. [PubMed: 29631086]
11. Ole Solheim., Tormod Selbekk., Store Jakola Asgeir., et al. Ultrasound-guided operations in unselected high-grade gliomas--overall results, impact of image quality and patient selection. Acta Neurochir 2010;152(11):1873–86. [PubMed: 20652608]
12. Riccabona M, Nelson TR, Weitzer C, et al. Potential of three-dimensional ultrasound in neonatal and paediatric neurosonography. Eur Radiol 2003;13(9):2082–93. [PubMed: 12928958]
13. Gronningsaeter A, Kleven A, Ommedal S, et al. SonoWand, an ultrasound-based neuronavigation system. Neurosurgery 2000;47(6):1373–9; discussion 1379–80. [PubMed: 11126908]
14. Hata N, Dohi T, Iseki H, et al. Development of a frameless and armless stereotactic neuronavigation system with ultrasonographic registration. Neurosurgery 1997;41(3):608–13; discussion 613–4. [PubMed: 9310978]
15. Laurence Mercier., Del Maestro Rolando F., Petrecca Kevin., et al. New prototype neuronavigation system based on preoperative imaging and intraoperative freehand ultrasound: system description and validation. Int J Comput Assist Radiol Surg 2011 ;6(4):507–22. [PubMed: 20886304]

16. Francesco Prada., Del Bene Massimiliano., Luca Mattei., et al. Fusion imaging for intra-operative ultrasound-based navigation in neurosurgery. J Ultrasound 2014;17(3):243–51. [PubMed: 25177400]
17. Magnus Berntsen Erik., Sasha Gulati., Ole Solheim., et al. Functional magnetic resonance imaging and diffusion tensor tractography incorporated into an intraoperative 3-dimensional ultrasound-based neuronavigation system: impact on therapeutic strategies, extent of resection, and clinical outcome. Neurosurgery 2010;67(2):251–64. [PubMed: 20644410]
18. Pierrick Coupé., Pierre Hellier., Xavier Morandi., et al. 3D Rigid Registration of Intraoperative Ultrasound and Preoperative MR Brain Images Based on Hyperechogenic Structures. Int J Biomed Imaging 2012;2012:531319. [PubMed: 22315583]
19. Inês Machado., Matthew Toews., Jie Luo., et al. Non-rigid registration of 3D ultrasound for neurosurgery using automatic feature detection and matching. Int J Comput Assist Radiol Surg 2018;13(10):1525–38. [PubMed: 29869321]
20. Frisken S, Luo M, Machado I, et al. Preliminary Results Comparing Thin Plate Splines with Finite Element Methods for Modeling Brain Deformation during Neurosurgery using Intraoperative Ultrasound. Proc SPIE Int Soc Opt Eng 2019;10951 Doi: 10.1117/12.2512799.
21. Inês Machado., Matthew Toews., Elizabeth George., et al. Deformable MRI-Ultrasound registration using correlation-based attribute matching for brain shift correction: Accuracy and generality in multi-site data. Neuroimage 2019;202:116094. [PubMed: 31446127]
22. Laurence Mercier., Vladimir Fonov., Claire Haegelen., et al. Comparing two approaches to rigid registration of three-dimensional ultrasound and magnetic resonance images for neurosurgery. Int J Comput Assist Radiol Surg 2012;7(1):125–36. [PubMed: 21633799]
23. Reinertsen I, Lindseth F, Unsgaard G, et al. Clinical validation of vessel-based registration for correction of brain-shift. Med Image Anal 2007;11(6):673–84. [PubMed: 17681484]
24. Tronnier VM, Bonsanto MM, Staubert A, et al. Comparison of intraoperative MR imaging and 3D-navigated ultrasonography in the detection and resection control of lesions. Neurosurg Focus 2001;10(2):E3.
25. van Velthoven V Intraoperative ultrasound imaging: comparison of pathomorphological findings in US versus CT, MRI and intraoperative findings. Acta Neurochir Suppl 2003;85:95–9. [PubMed: 12570143]
26. Tormod Selbekk., Store Jakola Asgeir., Ole Solheim., et al. Ultrasound imaging in neurosurgery: approaches to minimize surgically induced image artefacts for improved resection control. Acta Neurochir 2013;155(6):973–80. [PubMed: 23459867]
27. Geirmund Unsgård., Millgård Sagberg Lisa, Sébastien Müller., et al. A new acoustic coupling fluid with ability to reduce ultrasound imaging artefacts in brain tumour surgery-a phase I study. Acta Neurochir 2019;161(7):1475–86. [PubMed: 31104122]
28. Sidhu Paul S., Vito Cantisani., Dietrich Christoph F., et al. The EFSUMB Guidelines and Recommendations for the Clinical Practice of Contrast-Enhanced Ultrasound (CEUS) in Non-Hepatic Applications: Update 2017 (Long Version). Ultraschall Med 2018;39(2):e2–44. [PubMed: 29510439]
29. Francesco Prada., Alessandro Perin., Alberto Martegani., et al. Intraoperative contrast-enhanced ultrasound for brain tumor surgery. Neurosurgery 2014;74(5):542–52; discussion 552. [PubMed: 24598809]
30. Del Bene Massimiliano., Alessandro Perin., Cecilia Casali., et al. Advanced Ultrasound Imaging in Glioma Surgery: Beyond Gray-Scale B-mode. Front Oncol 2018;8:576. [PubMed: 30560090]
31. Rahul Sastry., Linda Bi Wenya., Steve Pieper., et al. Applications of Ultrasound in the Resection of Brain Tumors. J Neuroimaging 01 2017;27(1):5–15. [PubMed: 27541694]
32. Jones Pamela S, Swearingen Brooke. Intraoperative MRI for Pituitary Adenomas. Neurosurg Clin N Am 2019;30(4):413–20. [PubMed: 31471048]
33. Schwartz RB, Hsu L, Wong TZ, et al. Intraoperative MR imaging guidance for intracranial neurosurgery: experience with the first 200 cases. Radiology 1999;211(2):477–88. [PubMed: 10228532]
34. Choudhri Asim F., Adeel Siddiqui., Paul Klimo Jr., et al. Intraoperative MRI in pediatric brain tumors. Pediatr Radiol 2015;45 Suppl 3:S397–405. [PubMed: 26346145]

35. Feigl Guenther C., Stefan Heckl., Marcel Kullmann., et al. Review of first clinical experiences with a 1.5 Tesla ceiling-mounted moveable intraoperative MRI system in Europe. Bosn J Basic Med Sci 2019;19(1):24–30. [PubMed: 30589401]
36. Nimsky C, Ganslandt O, von Keller B, et al. Preliminary experience in glioma surgery with intraoperative high-field MRI. Acta Neurochir Suppl 2003;88:21–9. [PubMed: 14531557]
37. Sutherland GR, Louw DF Intraoperative MRI: a moving magnet. CMAJ 1999;161(10):1293. [PubMed: 10584095]
38. Sutherland GR, Kaibara T, Louw D, et al. A mobile high-field magnetic resonance system for neurosurgery. J Neurosurg 1999;91(5):804–13. [PubMed: 10541238]
39. Arya Nabavi., Lutz Dörner., Stark Andreas M., et al. Intraoperative MRI with 1.5 Tesla in neurosurgery. Neurosurg Clin N Am 2009;20(2):163–71. [PubMed: 19555878]
40. Michel Lacroix., Dima Abi-Said., Fourney Daryl R., et al. A multivariate analysis of 416 patients with glioblastoma multiforme: prognosis, extent of resection, and survival. J Neurosurg 2001;95(2):190–8.
41. Nader Sanai., Mei-Yin Polley., McDermott Michael W., et al. An extent of resection threshold for newly diagnosed glioblastomas. J Neurosurg 2011;115(1):3–8. [PubMed: 21417701]
42. Grabowski Matthew M., Recinos Pablo F., Nowacki Amy S., et al. Residual tumor volume versus extent of resection: predictors of survival after surgery for glioblastoma. J Neurosurg 2014;121(5):1115–23. [PubMed: 25192475]
43. Christian Senft., Andrea Bink., Kea Franz., et al. Intraoperative MRI guidance and extent of resection in glioma surgery: a randomised, controlled trial. Lancet Oncol 2011;12(11):997–1003. [PubMed: 21868284]
44. Aziz Hatiboglu Mustafa., Weinberg Jeffrey S., Dima Suki., et al. Impact of intraoperative high-field magnetic resonance imaging guidance on glioma surgery: a prospective volumetric analysis. Neurosurgery 2009;64(6):1073–81; discussion 1081. [PubMed: 19487886]
45. Molinaro Annette M., Shawn Hervey-Jumper., Morshed Ramin A., et al. Association of Maximal Extent of Resection of Contrast-Enhanced and Non-Contrast-Enhanced Tumor With Survival Within Molecular Subgroups of Patients With Newly Diagnosed Glioblastoma. JAMA Oncology 2020:495 Doi: 10.1001/jamaoncol.2019.6143.
46. Jason Beiko., Dima Suki., Hess Kenneth R., et al. IDH1 mutant malignant astrocytomas are more amenable to surgical resection and have a survival benefit associated with maximal surgical resection. Neuro Oncol 2014;16(1):81–91. [PubMed: 24305719]
47. Moriarty TM, Quinones-Hinojosa A, Larson PS, et al. Frameless stereotactic neurosurgery using intraoperative magnetic resonance imaging: stereotactic brain biopsy. Neurosurgery 2000;47(5):1138–45; discussion 1145–6. [PubMed: 11063107]
48. Bernays René L, Kollias Spyros S, Nadia Khan., et al. Histological yield, complications, and technological considerations in 114 consecutive frameless stereotactic biopsy procedures aided by open intraoperative magnetic resonance imaging. Journal of Neurosurgery 2002:354–62. Doi: 10.3171/jns.2002.97.2.0354. [PubMed: 12186464]
49. Marcin Czyż., Paweł Tabakow., Włodzimierz Jarmundowicz., et al. Intraoperative magnetic resonance-guided frameless stereotactic biopsies--initial clinical experience. Neurol Neurochir Pol 2012;46(2):157–60. [PubMed: 22581597]
50. Ekkehart Vitzthum Hans., Dirk Winkler., Gero Strauss., et al. NEUROGATE ® : a new MR-compatible device for realizing minimally invasive treatment of intracerebral tumors. Computer Aided Surgery 2004:45–50. Doi: 10.1080/10929080400006358. [PubMed: 15792936]
51. Larson Paul S., Starr Philip A., Geoffrey Bates., et al. An optimized system for interventional magnetic resonance imaging-guided stereotactic surgery: preliminary evaluation of targeting accuracy. Neurosurgery 2012;70(1 Suppl Operative):95–103; discussion 103. [PubMed: 21796000]
52. Jiri Bartek Jr., Ali Alattar., Margret Jensdottir., et al. Biopsy and Ablation of H3K27 Glioma Using Skull-Mounted Smartframe Device: Technical Case Report. World Neurosurg 2019;127:436–41. [PubMed: 30974271]
53. Hall WA, Martin AJ, Liu H, et al. Brain biopsy using high-field strength interventional magnetic resonance imaging. Neurosurgery 1999;44(4):807–13; discussion 813–4. [PubMed: 10201306]

54. Hall Walter A., Alastair Martin., Haiying Liu., et al. Improving diagnostic yield in brain biopsy: Coupling spectroscopic targeting with real-time needle placement. J Magn Reson Imaging 2001;13(1):12–5. [PubMed: 11169797]
55. Hornback NB Historical aspects of hyperthermia in cancer therapy. Radiol Clin North Am 1989;27(3):481–8.
56. Titsworth William Lee., Murad Greg J. A., Hoh Brian L., et al. Fighting fire with fire: the revival of thermotherapy for gliomas. Anticancer Res 2014;34(2):565–74. [PubMed: 24510985]
57. Cavaliere R, Ciocatto EC, Giovanella BC, et al. Selective heat sensitivity of cancer cells. Biochemical and clinical studies. Cancer 1967;20(9):1351–81. [PubMed: 4292219]
58. Curry Daniel J., Ashok Gowda., McNichols Roger J., et al. MR-guided stereotactic laser ablation of epileptogenic foci in children. Epilepsy Behav 2012;24(4):408–14. [PubMed: 22687387]
59. Alexandre Carpentier., McNichols Roger J., Jason Stafford R.., et al. Real-time magnetic resonance-guided laser thermal therapy for focal metastatic brain tumors. Neurosurgery 2008;63(1 Suppl 1):ONS21–8; discussion ONS28–9. [PubMed: 18728600]
60. Hans-Joachim Schwarzmaier., Frank Eickmeyer., Wernholt von Tempelhoff., et al. MR-guided laser-induced interstitial thermotherapy of recurrent glioblastoma multiforme: preliminary results in 16 patients. Eur J Radiol 2006;59(2):208–15. [PubMed: 16854549]
61. Thomas Jonathan G., Ganesh Rao., Yvonne Kew., et al. Laser interstitial thermal therapy for newly diagnosed and recurrent glioblastoma. Neurosurg Focus 2016;41(4):E12.
62. Manmeet Ahluwalia., Barnett Gene H., Di Deng., et al. Laser ablation after stereotactic radiosurgery: a multicenter prospective study in patients with metastatic brain tumors and radiation necrosis. J Neurosurg 2018;130(3):804–11. [PubMed: 29726782]
63. Medvid R, Ruiz A, Komotar RJ, et al. Current Applications of MRI-Guided Laser Interstitial Thermal Therapy in the Treatment of Brain Neoplasms and Epilepsy: A Radiologic and Neurosurgical Overview. American Journal of Neuroradiology 2015:1998–2006. Doi: 10.3174/ajnr.a4362. [PubMed: 26113069]
64. LaRiviere Michael J., Gross Robert E. Stereotactic Laser Ablation for Medically Intractable Epilepsy: The Next Generation of Minimally Invasive Epilepsy Surgery. Frontiers in Surgery 2016 Doi: 10.3389/fsurg.2016.00064.
65. Purvee Patel., Patel Nitesh V., Danish Shabbar F. Intracranial MR-guided laser-induced thermal therapy: single-center experience with the Visualase thermal therapy system. J Neurosurg 2016;125(4):853–60. [PubMed: 26722845]
66. Sloan Andrew E., Ahluwalia Manmeet S., Jose Valerio-Pascua., et al. Results of the NeuroBlate System first-in-humans Phase I clinical trial for recurrent glioblastoma. J Neurosurg 2013;118(6):1202–19. [PubMed: 23560574]
67. Usama Salem., Kumar Vinodh A., Madewell John E., et al. Neurosurgical applications of MRI guided laser interstitial thermal therapy (LITT). Cancer Imaging 2019;19(1):65. [PubMed: 31615562]
68. Shalit MN, Israeli Y, Matz S, et al. Experience with intraoperative CT scanning in brain tumors. Surg Neurol 1982;17(5):376–82. [PubMed: 6283689]
69. Christian Schichor., Nicole Terpolilli., Jun Thorsteinsdottir., et al. Intraoperative Computed Tomography in Cranial Neurosurgery. Neurosurg Clin N Am 2017;28(4):595–602. [PubMed: 28917287]
70. Conley David B, Bruce Tan., Bendok Bernard R., et al. Comparison of Intraoperative Portable CT Scanners in Skull Base and Endoscopic Sinus Surgery: Single Center Case Series. Skull Base 2011;21(4):261–70. [PubMed: 22470270]
71. Giuseppe Barbagallo., Massimiliano Maione., Simone Peschillo., et al. Intraoperative Computed Tomography, navigated ultrasound, 5-Amino-Levulinic Acid fluorescence and neuromonitoring in brain tumor surgery: overtreatment or useful tool combination? J Neurosurg Sci 2019 Doi: 10.23736/S0390-5616.19.04735-0.
72. Barbara Carl., Miriam Bopp., Benjamin Saß., et al. Reliable navigation registration in cranial and spine surgery based on intraoperative computed tomography. Neurosurg Focus 2019;47(6):E11.

Synopsis:

This chapter includes intraoperative imaging techniques used during high-grade glioma surgery. Intraoperative imaging helps to alleviate problems encountered during glioma surgery such as brain shift and residual tumor. The chapter starts with a brief introduction followed by a review with the latest advances in intraoperative ultrasound, intraoperative MRI, and intraoperative CT.

Key Points:

Intraoperative imaging allows accommodation of brain shift, identifies residual tumor and increases extent of resection. Intraoperative imaging techniques include ultrasound, MRI and CT.

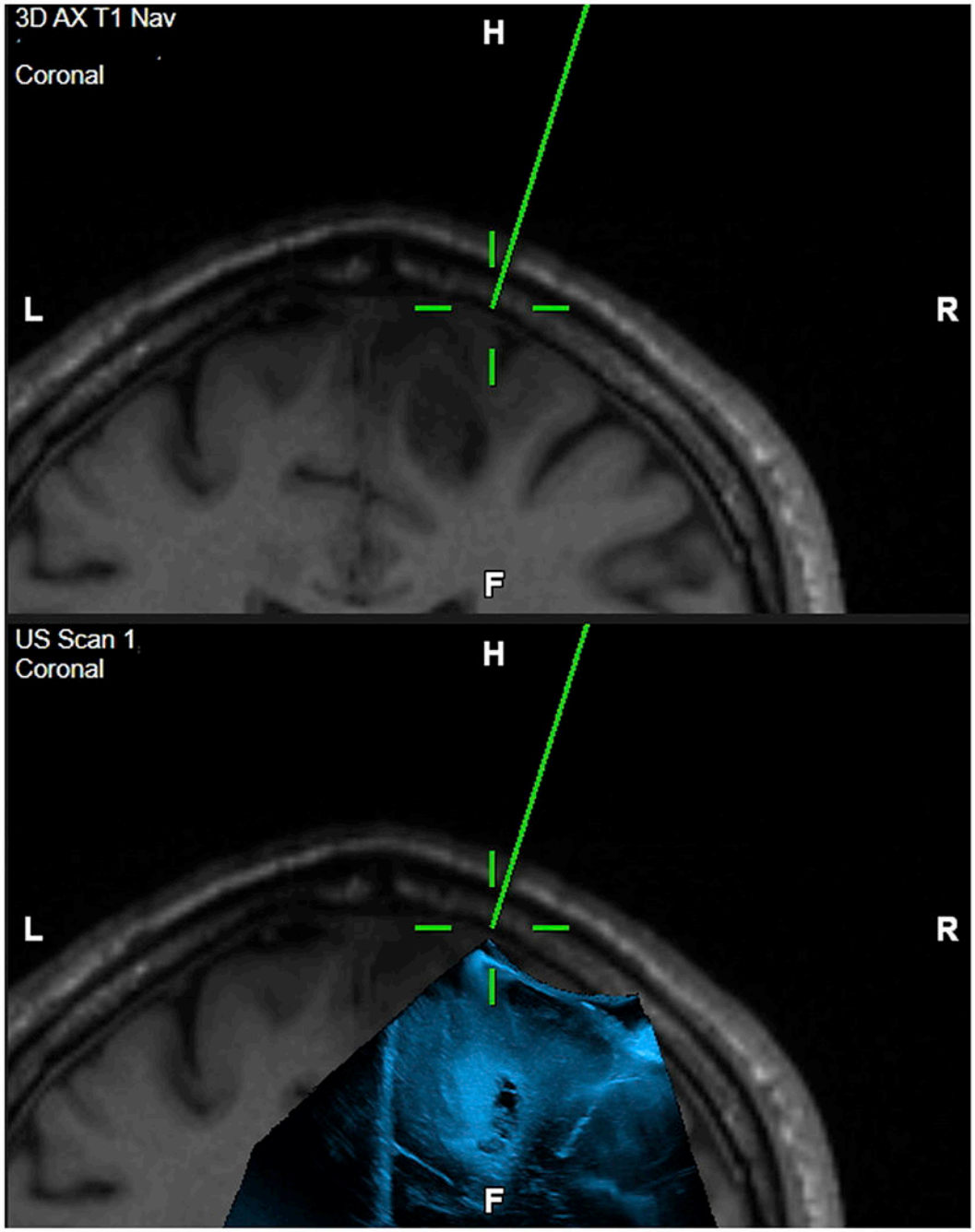

Fig. 1.

Navigated iUS fused to a preoperative T1-weighted MRI image of a glioma. Navigated iUS allows for accommodation of brain shift showing shift of the hyperechoic tumor relative to the registered preoperative MRI.

Fig. 2.
The AMIGO suite for image-guided surgery at Brigham and Women's Hospital.

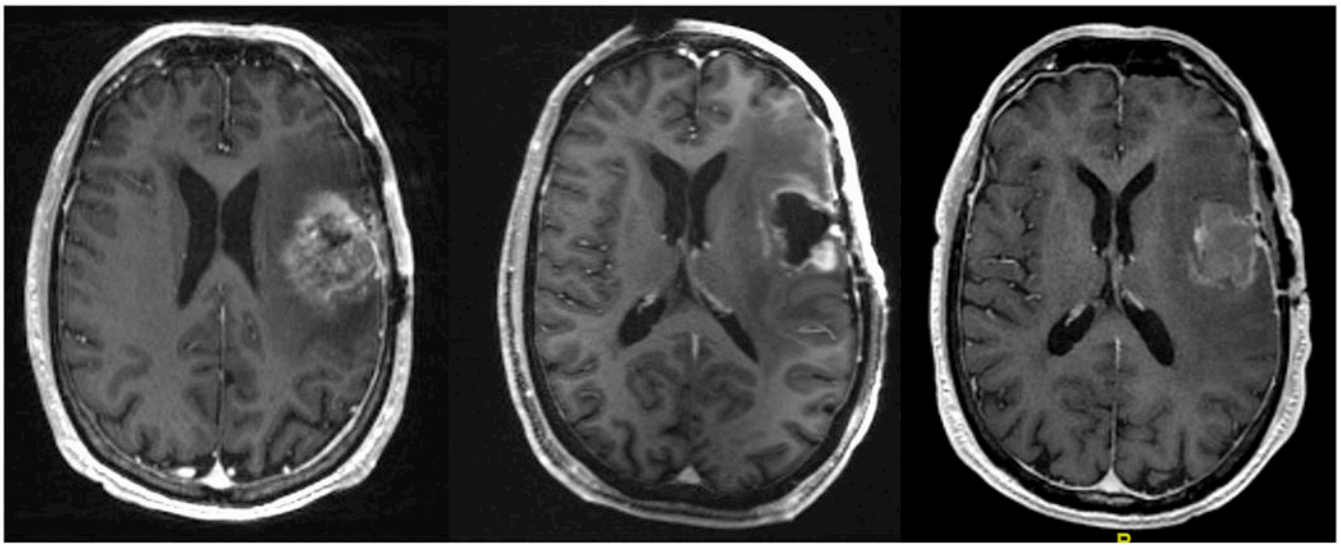

Fig. 3.

Preoperative contrast-enhanced T1-weighted MRI of a recurrent GBM (*left*), intraoperative contrast-enhanced T1-weighted MRI showing residual tumor under the lip of the resection edge (*middle*), postoperative T1-weighted contrasted MRI showing gross total resection of enhancing tumor (*right*).

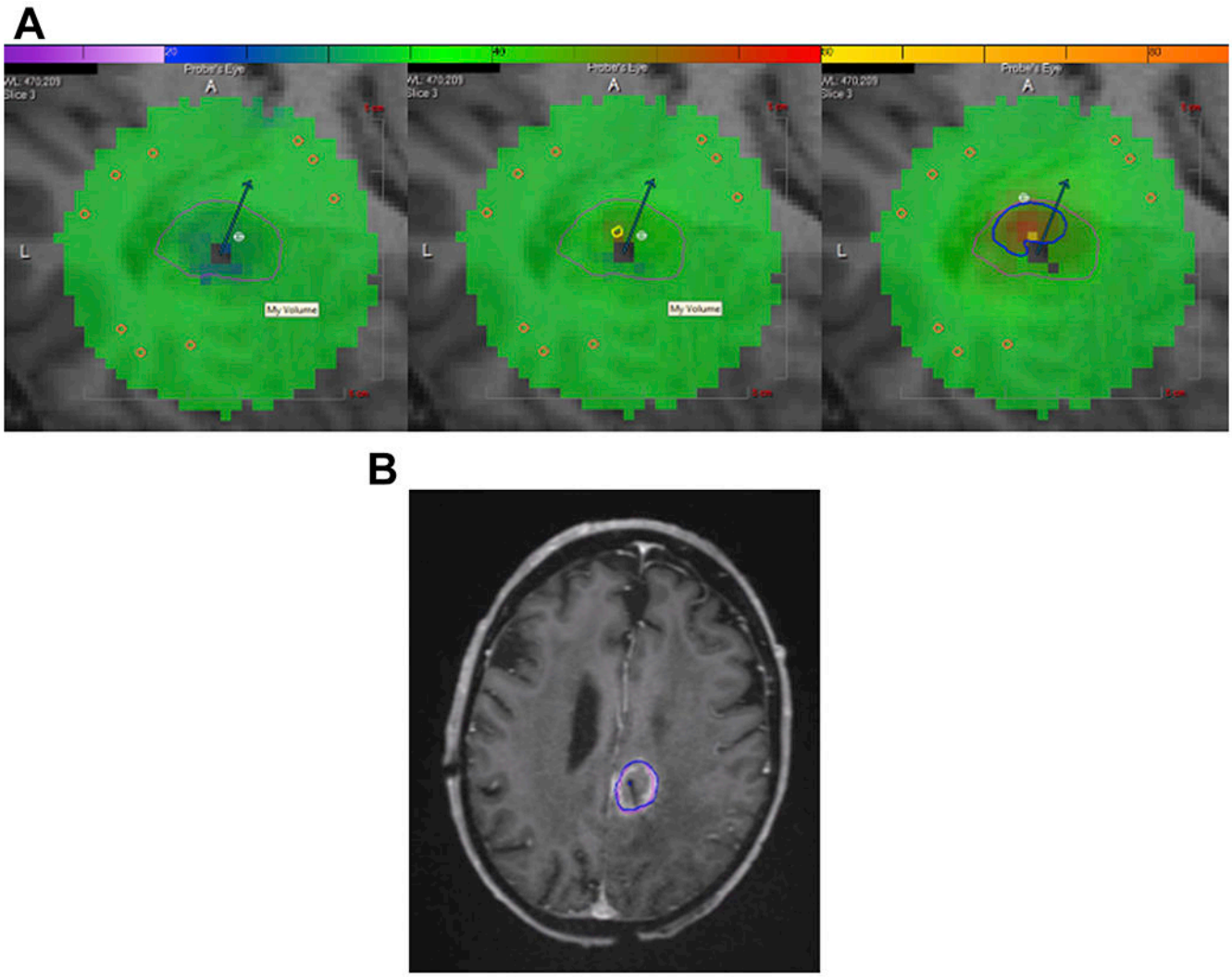

Fig. 4.

(*A*) Magnetic resonance thermometry allows the operator to assess relative temperature maps in real-time. The three panels are the same slice taken at different time points in the ablation. (*Left*) The tumor (*pink outline*) preablation with a cooler center (*bluish hue*) as cooled CO_2 is sent around the catheter tip. (*Middle*) The same slice midablation with a relative warming up of the center of the catheter (*greenish hue*) and the beginnings of the thermal damage estimate beginning to appear (*yellow*). (*Right*) Further warming (*reddish hue*) and larger thermal damage estimate. (*B*) LITT ablation procedure performed in iMRI using magnetic resonance thermometry sequences to derive thermal damage estimates.