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Intraoperative Imaging in Neurosurgery: Where Will the Future Take Us?

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Abstract

Intraoperative MRI (ioMRI) dates back to the 1990s and since then has been successfully applied in neurosurgery for three primary reasons with the last one becoming the most significant today: (1) brain shift-corrected navigation, (2) monitoring/controlling thermal ablations, and (3) identifying residual tumor for resection. IoMRI, which today is moving into other applications, including treatment of vasculature and the spine, requires advanced 3 T MRI platforms for faster and more flexible image acquisitions, higher image quality, and better spatial and temporal resolution; functional capabilities including fMRI and DTI; non-rigid registration algorithms to register pre- and intraoperative images; non-MRI imaging improvements to continuously monitor brain shift to identify when a new 3D MRI data set is needed intraoperatively; more integration of imaging and MRI-compatible navigational and robot-assisted systems; and greater computational capabilities to handle the processing of data. The Brigham and Women's Hospital's "AMIGO" suite is described as a setting for progress to continue in ioMRI by incorporating other modalities including molecular imaging. A call to action is made to have other researchers and clinicians in the field of image guided therapy to work together to integrate imaging with therapy delivery systems (such as laser, MRgFUS, endoscopic, and robotic surgery devices).

Keywords

Image guided therapy; Imaging; Interventional; Intraoperative MRI (ioMRI); Magnetic resonance; MR; Neurosurgery

Introduction

Since the early 1990s when we introduced intraoperative MRI (ioMRI) to the field of neurosurgery, it has greatly developed and the number of users and clinical applications have increased [1–10]. It is now important to look back and evaluate the progress of ioMRI to assess what has happened during almost two decades of activity and to identify to the best of our abilities where we are headed.

The original reasons to develop ioMRI were the following:

1. Brain shift-corrected navigation: The navigational systems used in operating rooms rely on preoperative images that do not reflect changes in brain anatomy due to deformations and shifts during surgery. This situation has caused inaccurate targeting and major limitations for neuronavigation. Today, by updating information on the brain using a 3D image database, navigation is made more accurate throughout the entire surgical procedure [11, 12].
2. Monitoring/controlling thermal ablations: The original idea of MRI-guided interstitial laser brain surgery leveraged the temperature sensitivity of MRI to allow for temperature monitoring during the procedure [13–20]. Today, radio-frequency (RF) and focused ultrasound thermal ablations can similarly be controlled through MRI [21–26].
3. Identifying residual tumor: MRI allows the clinician to verify completeness of tumor removal at the end of surgery and, if needed, to perform an additional tumor resection. The original vision for ioMRI focused on correcting for brain shift and monitoring temperature, while today most users apply to perform ioMRI for the third reason: tumor control [4, 27–29].

Since its introduction, ioMRI, conceptually and in real practice, has grown and changed significantly.

Present Benefits and Capabilities

The original full access open MRI, like the SIGNA SP (General Electric Healthcare Technologies, Waukesha, WI), was replaced with open limited access low and midfield magnets and high (1.5 T) and ultra high field (3 T) closed bore MRI scanners [6, 9, 10, 30–32]. Although, the SIGNA SP represented the best configuration, it is at midfield and, therefore, not optimal for neurosurgery. Today most neurosurgeons want higher field strength and more advanced image acquisition technology that is only available in high field advanced systems to obtain higher image quality and better spatial and temporal resolution.

Advanced 3 T imaging platforms achieve faster and more flexible image acquisitions that improve localization, targeting, monitoring, and therapy control. Advance imaging methods functional MRI (fMRI) and diffusion tensor imaging (DTI) have been introduced into neurosurgery and integrated into intraoperative imaging [33–35].

As far as clinical applications are concerned, ioMRI has been successfully developed and implemented for multiple procedures, including:

- Biopsies and placement of electrodes
- Craniotomies for image-guided resection of benign and malignant intracranial tumors
- Intracranial cyst drainages and
- Thermal ablations for malignant and benign tumors.

Future ioMRI Applications

In the future, this application pool will expand to:

Benign tumors (skull base): MRI-enhanced neuroendoscopy can be faster and safer than conventional neuroendoscopy and minimize the possibility of complications. A strong need exists to develop MRI-compatible flexible endoscopes with position tracking coils. The combination of the two techniques may provide the best surgical guidance. The most promising application is endoscopic transphenoidal surgery for midline skull base and parasellar lesions and transventricular endoscopic removal for extra-ventricular tumors.

Neurovascular abnormalities and stroke: ioMRI provides real-time perfusion and diffusion imaging to intraoperatively diagnose acutely developed vascular occlusion and to monitor the condition of the brain during surgeries and/or endovascular procedures. Intraoperative imaging of vascular anatomy, including feeding arteries and the draining veins of an intracranial arteriovenous malformation (AVM), allows the neurosurgeon to intraoperatively assess vessels and surrounding areas and make decisions about the need to completely and safely resect or obliterate a vascular malformation.

Various diseases of the spine: Spinal surgeries with IMR will include: lumbar discectomies, anterior cervical discectomies with fusion, cervical vertebrectomies, foraminotomies, and laminectomies. Through ioMRI, the accuracy of localization and adequacy of decompression can be assessed. Future applications may also include: resection of spine and spinal cord, tumors, and spinal endoscopy. Temperature sensitive imaging for laser discectomy and vertebroplasty can be performed with ioMRI guidance to prevent the thermal damage of the nerve roots and spinal cord.

ioMRI Approaches

The “tumor control” method of ioMRI is a practical and well accepted use of the technology, though it is best applied, not as a single imaging session at the completion of surgery when the clinician cannot take full advantage of ioMRI, but throughout surgery to provide corrected, brain shift-compensated guidance (with serial imaging and navigation). The goal of more complete and effective tumor resection can only be accomplished if we have better techniques to detect the full extent of infiltrative brain tumors. ioMRI is part of this solution along with other multimodality-based molecular imaging (optical, nuclear, or other). Besides tumor margin detection, we need more detailed information about the functional and structural anatomy of the normal brain tissue that surrounds the tumor (for MRI such detail comes through multiparametric imaging: T1, T2, fMRI, DTI perfusion imaging).

Managing the Brain Shift Challenge

Navigational systems fully integrated with ioMRI are also part of improved image guidance [8, 11, 36–39]. For example, it is necessary to monitor brain shift with a non-MRI technique for continuous monitoring that helps the surgeon/neuroradiologist to decide when a new

MRI 3D dataset should be obtained. Development of an integrated system to improve visualization, navigation, and monitoring is a necessary step in this direction.

Today we know it is possible to create an augmented reality visualization of the intraoperative configuration of the patient's brain merged with high resolution preoperative imaging data, including DTI and fMRI to better localize the tumor and critical healthy tissues. Brain shift-corrected imaging requires the use of non-rigid registration algorithms to compensate for displacements [40–42]. Massive computational needs must support these capabilities that entail online usage in reasonable time frames of less than 5 min. One of the main reasons for this computational load is that, to properly account for ongoing brain shifts, fMRI and DTI must be accurately co-registered and updated.

Methods of monitoring brain shift now include:

Laser Range Scanner (LRS): Devices, mostly used in robotics applications, that emit and receive a laser beam and by measuring difference of phase, time of flight or frequency shift depth is measured.

Stereo camera imaging: Imaging from a type of camera with two or more lenses that can capture three-dimensional images.

Transcranial US (iTUM): A type of device, at the prototype stage, that uses the shear mode of transcranial ultrasound transmission to intraoperatively monitor brain shift. MRI can then be obtained with the device spatially registered to the MRI reference coordinates [43].

Further Development

ioMRI allows for the introduction of new surgical approaches and/or techniques in vascular neurosurgery, spine surgery, and skull base surgery (using image guided and registered neuroendoscopy). Further moving ioMRI forward in neurosurgery is the already-underway integration of ioMRI with image guided robots that provide, through remote manipulation, an alternative solution to limited access. Already, for many types of neurosurgical procedures, companies have developed MRI-compatible robotic systems and manipulators [44–51]. Today most systems still lack the clinical validation that is necessary for the surgical robot to execute not only biopsies but also complex surgical manipulations.

ioMRI today has also moved beyond MRI-guided and controlled thermal ablations for interstitial laser therapy [13, 14, 16, 17, 19] to MRI-guided focused ultrasound surgery (MRgFUS) as well as the targeted ablative treatment of brain tumors via drug delivery through an open blood-brain-barrier (BBB) [23–25, 52–57]. FUS-induced neuromodulation is a complement to functional neurosurgical applications for coagulative lesions [57–59].

Greater progress and expansion for ioMRI requires the development of new, more advanced imaging methods, navigational techniques, surgical instruments and tools; the more efficient use of computing technologies; and the integration of diagnostic and therapy devices with navigational tools (computer-assisted surgery). A need exists for a multi-focused,

multidisciplinary effort involving researchers and clinicians to explore and refine ioMRI to make it as cost-effective and as widely accessible to a multidisciplinary pool of users.

AMIGO: Merging ioMRI and Other Modalities

At the Brigham and Women's Hospital, we are taking a lead in this effort through the development and execution of a multimodality approach to intraoperative imaging by integrating the components of a rich multimodal and translational clinical research environment to carry out open and minimally invasive surgeries and percutaneous interventions. Multimodality IGT provides comprehensive information derived from different physical and biological properties. Combined multimodalities provide anatomical, metabolic, and functional information – a previously stated goal for ioMRI. Images can be complemented with newly developed multiple molecular probes (nuclear, optical, mass spectrometer, etc.). The use of multiple molecular probes improves the sensitivity and specificity of cancer-relevant applications over single mode imaging. To achieve this we must expand our imaging platform for image guided neurosurgery to include all modalities, especially those applicable to molecular imaging (PETCT, MRI, optical imaging).

The validation of imaging tools and molecular imaging agents in a multimodal surgical setting is possible because, during surgeries, multiple tissue samples can be obtained for pathology that can validate imaging findings at the same location. Navigational and registration methods for multimodal registration can be used to compare multiple probes that are measuring exactly the same tissue region.

The BWH's Advanced Multimodality Image Guided Operating (AMIGO) Suite (see Fig. 1), opening in 2010, is uniquely designed to support, alongside routine clinical procedures, the next phase of clinical and research activity in ioMRI that will incorporate multimodal imaging. The logistics of the suite are such that multidisciplinary teams will be in close cooperation with one another during procedures that might involve the use of an array of on-site (i.e., in the suite itself) modalities from 3D ultrasound, fluoroscopy, MRI, and PET/CT to carry out a variety of procedures.

The AMIGO and suites like it are at the forefront by providing settings for practice, refinement, improvement, validation, and innovation. Indeed, the future of intraoperative imaging in neurosurgery depends on such settings and teams and their increased application of advanced technologies and multimodality imaging. Integration of imaging with therapy delivery systems (laser, MRgFUS, endoscopic and robotic surgery devices) will characterize the next phase of this emerging field.

References

1. Black PM, Alexander E 3rd, Martin C, et al. Craniotomy for tumor treatment in an intraoperative magnetic resonance imaging unit. *Neurosurgery*. 1999; 45(3):423–431. [PubMed: 10493363]
2. Dimaio SP, Archip N, Hata N, et al. Image-guided neurosurgery at Brigham and Women's Hospital. *IEEE Eng Med Biol Mag*. 2006; 25(5):67–73. [PubMed: 17020201]
3. Hall WA, Martin AJ, Liu H, et al. High-field strength interventional magnetic resonance imaging for pediatric neurosurgery. *Pediatr Neurosurg*. 1998; 29(5):253–259. [PubMed: 9917543]

4. Jolesz FA, Talos IF, Schwartz RB, et al. Intraoperative magnetic resonance imaging and magnetic resonance imaging-guided therapy for brain tumors. *Neuroimaging Clin N Am*. 2002; 12 (4):665–683. [PubMed: 12687918]
5. Lewin JS, Metzger AK. Intraoperative MR systems. Low-field approaches. *Neuroimaging Clin N Am*. 2001; 11(4):611–628. [PubMed: 11995417]
6. Schenck JF, Jolesz FA, Roemer PB, Cline HE, Lorensen WE, Kikinis R, et al. Superconducting open-configuration MR imaging system for image-guided therapy. *Radiology*. 1995; 195 (3):805–814. [PubMed: 7754014]
7. 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):477–488. [PubMed: 10228532]
8. Schulder M, Liang D, Carmel PW. Cranial surgery navigation aided by a compact intraoperative magnetic resonance imager. *J Neurosurg*. 2001; 94(6):936–945. [PubMed: 11409523]
9. Steinmeier R, Fahlbusch R, Ganslandt O, et al. Intraoperative magnetic resonance imaging with the magnetom open scanner: concepts, neurosurgical indications, and procedures: a preliminary report. *Neurosurgery*. 1998; 43(4):739–747. discussion 747–748. [PubMed: 9766299]
10. Sutherland GR, Kaibara T, Louw D, Hoult DI, Tomanek B, Saunders J. A mobile high-field magnetic resonance system for neurosurgery. *J Neurosurg*. 1999; 91(5):804–813. [PubMed: 10541238]
11. Jolesz FA, Kikinis R, Talos IF. Neuronavigation in interventional MR imaging. Frameless stereotaxy. *Neuroimaging Clin N Am*. 2001; 11(4):685–689. [PubMed: 11995423]
12. Nabavi A, Black PM, Gering DT, et al. Serial intraoperative magnetic resonance imaging of brain shift. *Neurosurgery*. 2001; 48 (4):787–797. discussion 797–798. [PubMed: 11322439]
13. Anzai Y, Lufkin R, DeSalles A, Hamilton DR, Farahani K, Black KL. Preliminary experience with MR-guided thermal ablation of brain tumors. *AJNR Am J Neuroradiol*. 1995; 16(1):39–48. discussion 49–52. [PubMed: 7900601]
14. Ascher PW, Justich E, Schröttner O. Interstitial thermotherapy of central brain tumors with the Nd:YAG laser under real-time monitoring by MRI. *J Clin Laser Med Surg*. 1991; 9(1):79–83. [PubMed: 10150912]
15. Bettag M, Ulrich F, Schober R, et al. Stereotactic laser therapy in cerebral gliomas. *Acta Neurochir Suppl (Wien)*. 1991; 52:81–83. [PubMed: 1792975]
16. Fan M, Ascher PW, Schröttner O, Ebner F, Germann RH, Kleinert R. Interstitial 1.06 Nd:YAG laser thermotherapy for brain tumors under real-time monitoring of MRI: experimental study and phase I clinical trial. *J Clin Laser Med Surg*. 1992; 10(5):355–356. [PubMed: 10147968]
17. Kahn T, Bettag M, Ulrich F, et al. MRI-guided laser-induced interstitial thermotherapy of cerebral neoplasms. *J Comput Assist Tomogr*. 1994; 18:519–532. [PubMed: 8040431]
18. Kettenbach J, Silverman SG, Hata N, et al. Monitoring and visualization techniques for MR-guided laser ablations in an open MR system. *J Magn Reson Imaging*. 1998; 8(4):933–943. [PubMed: 9702896]
19. McDannold NJ, Jolesz FA. Magnetic resonance image-guided thermal ablations. *Top Magn Reson Imaging*. 2000; 11(3):191–202. [PubMed: 11145211]
20. Stollberger R, Ascher PW, Huber D, Renhart W, Radner H, Ebner F. Temperature monitoring of interstitial thermal tissue coagulation using MR phase images. *J Magn Reson Imaging*. 1998; 8(1):188–196. [PubMed: 9500279]
21. Cline HE, Hynynen K, Watkins RD, et al. Focused US system for MR imaging-guided tumor ablation. *Radiology*. 1995; 194 (3):731–737. [PubMed: 7862971]
22. Hynynen K, Vykhodtseva NI, Chung AH, Sorrentino V, Colucci V, Jolesz FA. Thermal effects of focused ultrasound on the brain: determination with MR imaging. *Radiology*. 1997; 204(1):247–253. [PubMed: 9205255]
23. Jolesz FA, Hynynen K. Magnetic resonance image-guided focused ultrasound surgery. *Cancer J*. 2002; 8(suppl 1):S100–S112. [PubMed: 12075696]
24. Jolesz FA, Hynynen K, McDannold N, Tempny C. MR imaging-controlled focused ultrasound ablation: a noninvasive image-guided surgery. *Magn Reson Imaging Clin N Am*. 2005; 13(3):545–60. [PubMed: 16084419]

25. Jolesz FA, McDannold N. Current status and future potential of MRI-guided focused ultrasound surgery. *J Magn Reson Imaging*. 2008; 27(2):391–399. [PubMed: 18219674]
26. McDannold N, Hynynen K, Wolf D, Wolf G, Jolesz F. MRI evaluation of thermal ablation of tumors with focused ultrasound. *J Magn Reson Imaging*. 1998; 8(1):91–100. [PubMed: 9500266]
27. Claus EB, Horlacher A, Hsu L. Survival rates in patients with low-grade glioma after intraoperative magnetic resonance image guidance. *Cancer*. 2005; 103(6):1227–1233. [PubMed: 15690327]
28. Mittal S, Black PM. Intraoperative magnetic resonance imaging in neurosurgery: the Brigham concept. *Acta Neurochir Suppl*. 2006; 98:77–86. [PubMed: 17009704]
29. Nimsy C, Fujita A, Ganslandt O, Von Keller B, Fahlbusch R. Volumetric assessment of glioma removal by intraoperative high-field magnetic resonance imaging. *Neurosurgery*. 2004; 55(2): 358–370. discussion 370–371. [PubMed: 15271242]
30. Bradley WG. Achieving gross total resection of brain tumors: intraoperative MR imaging can make a big difference. *AJNR Am J Neuroradiol*. 2002; 23(3):348–349. [PubMed: 11900997]
31. Nimsy C, Ganslandt O, Von Keller B, Romstöck J, Fahlbusch R. Intraoperative high-field-strength MR imaging: implementation and experience in 200 patients. *Radiology*. 2004; 233(1): 67–78. [PubMed: 15317949]
32. Truwit CL, Hall WA. Intraoperative magnetic resonance imaging-guided neurosurgery at 3-T. *Neurosurgery*. 2006; 58(4 suppl 2):ONS-338–345. discussion ONS-345–346.
33. Hall WA, Liu H, Truwit CL. Functional magnetic resonance imaging-guided resection of low-grade gliomas. *Surg Neurol*. 2005; 64(1):20–27. discussion. [PubMed: 15993174]
34. Golby, AJ.; McConnell, KA. Functional brain mapping options for minimally invasive surgery. In: Black, PM.; Proctor, M., editors. *Minimally invasive neurosurgery*. Humana Press; Totawa, NJ: 2004. p. 87-106.
35. Nimsy C, Ganslandt O, Kober H, et al. Integration of functional magnetic resonance imaging supported by magnetoencephalography in functional neuronavigation. *Neurosurgery*. 1999; 44 (6): 1249–1255. discussion 1255–1256. [PubMed: 10371623]
36. Gering DT, Nabavi A, Kikinis R, et al. An integrated visualization system for surgical planning and guidance using image fusion and an open MR. *J Magn Reson Imaging*. 2001; 13(6):967–975. [PubMed: 11382961]
37. Nabavi A, Gering DT, Kacher DF, et al. Surgical navigation in the open MRI. *Acta Neurochir Suppl*. 2003; 85:121–125. [PubMed: 12570147]
38. Nimsy C, Ganslandt O, Cerny S, Hastreiter P, Greiner G, Fahlbusch R. Quantification of, visualization of, and compensation for brain shift using intraoperative magnetic resonance imaging. *Neurosurgery*. 2000; 47(5):1070–1079. discussion 1079–1080. [PubMed: 11063099]
39. Nimsy C, Ganslandt O, Hastreiter P, Fahlbusch R. Intraoperative compensation for brain shift. *Surg Neurol*. 2001; 56(6):357–364. discussion 364–365. [PubMed: 11755962]
40. Clatz O, Delingette H, Talos IF, et al. Hybrid formulation of the model-based non-rigid registration problem to improve accuracy and robustness. *Med Image Comput Comput Assist Interv*. 2005; 8(Pt 2):295–302. [PubMed: 16685972]
41. Ferrant M, Nabavi A, Macq B, et al. Serial registration of intraoperative MR images of the brain. *Med Image Anal*. 2002; 6(4):337–359. [PubMed: 12426109]
42. Warfield SK, Haker SJ, Talos IF, et al. Capturing intraoperative deformations: research experience at Brigham and Women's Hospital. *Med Image Anal*. 2005; 9(2):145–162. [PubMed: 15721230]
43. White PJ, Whalen S, Tang SC, Clement G, Jolesz F, Golby AJ. An intraoperative brain shift monitor using shear mode transcranial ultrasound: preliminary results. *J Ultrasound Med*. 2009; 28(2):191–203. [PubMed: 19168769]
44. Chinzei K, Miller K. Towards MRI guided surgical manipulator. *Med Sci Monit*. 2001; 7(1):153–163. [PubMed: 11208513]
45. Chinzei K, Warfield S, Hata N, Tempny C, Jolesz F, Kikinis R. Planning, simulation and assistance with intraoperative MRI. *Minim Invasive Ther Allied Technol*. 2003; 12(1):59–64. [PubMed: 16754079]

46. DiMaio SP, Pieper S, Chinzei K, et al. Robot-assisted needle placement in open MRI: system architecture, integration and validation. *Comput Aided Surg.* 2007; 12(1):15–24. [PubMed: 17364655]
47. Elhawary H, Tse ZT, Hamed A, Rea M, Davies BL, Lamperth MU. The case for MR-compatible robotics: a review of the state of the art. *Int J Med Robot.* 2008; 4(2):105–113. [PubMed: 18481822]
48. Elhawary H, Zivanovic A, Davies B, Lampérth M. A review of magnetic resonance imaging compatible manipulators in surgery. *Proc Inst Mech Eng.* 2006; 220(3):413–424.
49. Masamune K, Kobayashi E. Development of an MRI-compatible needle insertion manipulator for stereotactic neurosurgery. *J Image Guid Surg.* 1995; 1(4):242–248. [PubMed: 9079451]
50. Sutherland GR, Latour I, Greer AD. Integrating an image-guided robot with intraoperative MRI: a review of the design and construction of neuroArm. *IEEE Eng Med Biol Mag.* 2008; 27(3):59–65. [PubMed: 18519183]
51. Sutherland GR, Latour I, Greer AD, Fielding T, Feil G, Newhook P. An image-guided magnetic resonance-compatible surgical robot. *Neurosurgery.* 2008; 62(2):286–292. discussion 292–293. [PubMed: 18382307]
52. Hynynen K, McDannold N, Vykhodtseva N, Jolesz FA. Noninvasive MR imaging-guided focal opening of the blood–brain barrier in rabbits. *Radiology.* 2001; 220(3):640–646. [PubMed: 11526261]
53. Kinoshita M, McDannold N, Jolesz FA, Hynynen K. Targeted delivery of antibodies through the blood–brain barrier by MRI-guided focused ultrasound. *Biochem Biophys Res Commun.* 2006; 340(4):1085–1090. [PubMed: 16403441]
54. Kinoshita M, McDannold N, Jolesz FA, Hynynen K. Non-invasive localized delivery of Herceptin to the mouse brain by MRI-guided focused ultrasound-induced blood–brain barrier disruption. *Proc Natl Acad Sci U S A.* 2006; 103(31):11719–11723. [PubMed: 16868082]
55. Treat LH, McDannold N, Vykhodtseva N, Zhang Y, Tam K, Hynynen K. Targeted delivery of doxorubicin to the rat brain at therapeutic levels using MRI-guided focused ultrasound. *Int J Cancer.* 2007; 121(4):901–907. [PubMed: 17437269]
56. Vykhodtseva N, McDannold N, Hynynen K. Induction of apoptosis in vivo in the rabbit brain with focused ultrasound and optison. *Ultrasound Med Biol.* 2006; 32(12):1923–1929. [PubMed: 17169704]
57. Yoo SS, Lee JH, Zhang Y, et al. FUS-mediated reversible modulation of region-specific brain function. *Proc MRgFUS.* 2008; 2008:10.
58. Colucci V, Strichartz G, Jolesz F, Vykhodtseva N, Hynynen K. Focused ultrasound effects on nerve action potential in vitro. *Ultrasound Med Biol.* 2009; 35(10):1737–1747. [PubMed: 19647923]
59. Currier DP, Greathouse D, Swift T. Sensory nerve conduction: effect of ultrasound. *Arch Phys Med Rehabil.* 1978; 59(4):181–185. [PubMed: 646607]

Fig. 1.

Advanced Multimodality Image Guided OR (AMIGO). The middle room is an operating room with surgical microscope, angiography, ultrasound and optical imaging. The room on the left has a PETCT and on the right a 3T MRI which is ceiling mounted and can move into the operating room to image the patient on the operating room table (IMRIS, Winnipeg, Canada)