Image-Guided Neurosurgery

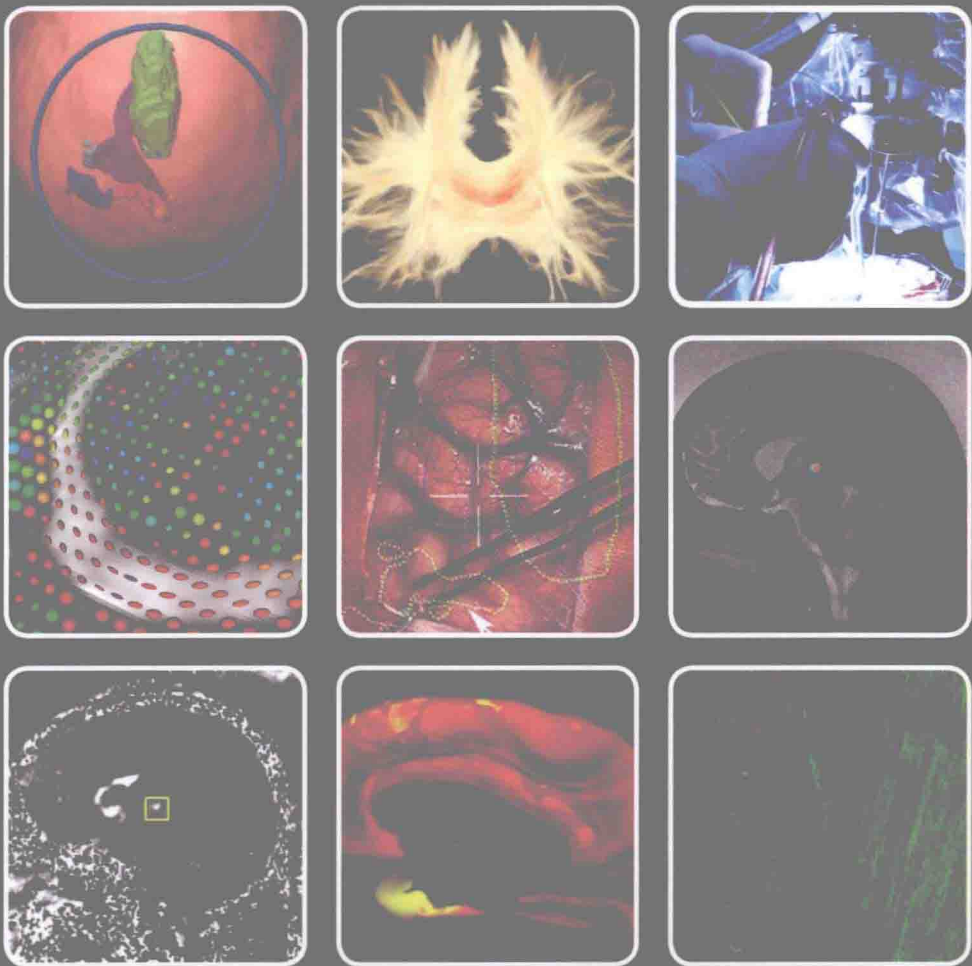

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IMAGE-GUIDED NEUROSURGERY

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DEDICATION

This book is dedicated to my mentor, colleague, and friend Ferenc Jolesz. Ferenc welcomed me to Brigham and Women's Hospital during the height of the world's first experiences with intra operative MRI. I was just starting my career and he provided me a most fertile environment in which to collaborate and develop innovative neurosurgical approaches.

Ferenc saw the broadest possible perspective of image guided therapy. Having trained first as a neurosurgeon and then as neuroradiologist, his soft spot was often in developing techniques for neurosurgery while taking full advantage of radiological innovations. This bias made us natural allies, and together we started our journey of understanding the complexity of the brain and of brain pathologies. Over the years, in addition to the MRT program and its follow-on, the AMIGO suite, he was powerfully involved in high intensity focused ultrasound, development of biomarkers for imaging, robotics for neurosurgery, and functional and structural mapping of the brain; I discussed nearly every topic represented in this book frequently with Ferenc. He introduced me personally to many of the authors of the chapters. He wrote the Foreword whilst recuperating from one of many interventions he had soldiered through for over two decades, his force undiminished, and as always, directed towards technical innovation and guiding and mentoring our close-knit team with interests across the whole spectrum of image guided therapies. Ferenc was a very special leader who will leave an indelible mark in neurosurgery as well as many other interventional specialties. This book brings some of that together in one place. I hope that it will serve as a key reference for many. It would have been Ferenc's greatest wish to see these ideas and technologies disseminated throughout the world.

FOREWORD

This book is the first in a decade to tackle the subject of image guidance in neurosurgery and to incorporate all current aspects and future potential of this wide-ranging and fast-advancing field. There are increasing numbers of users of image-guided technology not only in neurosurgery but also in other surgical fields and new clinical applications are constantly evolving. This book will help the reader to understand all the current proven advantages and future perspectives across the full range of image-guided techniques in neurosurgery and at the same time become familiar with the wide variety of already existing and only foreseen clinical applications.

Since its introduction in the early 1990s intraoperative MRI (iMRI) has substantively changed modern neurosurgery. The vision and inspiration of iMRI was the direct consequence of the widespread acceptance of MRI as the primary method of diagnostic neuroimaging. Since then iMRI has followed the progress of MRI technology and has grown with its advances. Before iMRI was introduced in neurosurgery it became obvious that there is a new and better way to guide and control interventions like biopsies and thermal ablations by MRI. That recognition of the power of MRI for nondiagnostic application is the origin of interventional MRI. The discovery of MRI-guided interstitial laser surgery and its potential to treat brain tumors was the initial motivation for the development of the first genuine iMRI designed almost exclusively for neurosurgical use by General Electric in collaboration with Brigham and Women's Hospital investigators.

At the time this groundbreaking new iMRI was installed, preoperative MRI-based computerized navigational methods were already customary in neurosurgery. However, their inability to maintain accuracy during surgeries in the presence of substantial brain shifts and deformations remained unresolved. It was recognized early that iMRI could provide a possible solution for the inherent problem of preoperative imaging-based navigation. Serial imaging during brain surgeries provides anatomically correct updates for navigation. The first iMRI system therefore integrated navigation with continuous multioblique image plane selection and also provided monitoring and control for thermal ablations using temperature-sensitive MRI. In addition to open craniotomies, biopsies, minimally invasive laser procedures, and endoscopies were performed in an open configuration environment with two neurosurgeons having full access to the head without the need for moving the patient. All these novel technological features and the optimal workflow environment made this system ideal for neurosurgical use, but the high cost and relatively low image quality precluded its broad adoption.

In the first decade of iMRI, several open and more or less closed magnet configurations with increasing field strength were tested for neurosurgical use by multiple investigators. In the end, closed magnets with higher field strength were the final choice of most academic neurosurgical centers. The reason for this choice has been the improvement of image quality achieved with advanced high-field MRI, which now dominates diagnostic neuroimaging. It is difficult to use a lower quality image during surgery compared with the preoperative diagnostic images that show much more detail. High-resolution imaging is particularly important for intraoperative guidance when visualization of intricate details is even more essential than in the diagnostic workup. Unfortunately, this requirement for better image quality and resolution has led to a major compromise. Higher field closed configuration magnets with superb image quality have become the choice of most neurosurgeons but the cost is a very inconvenient environment requiring a complicated workflow that limits what can be accomplished during a surgical session. Requirements of the closed bore include moving the patient deep into the bore of the magnet or moving the magnet to the patient on the operating room table in order to obtain images. More importantly, with this approach, one must give up one of the main advantages of iMRI: to provide imaging updates by serial imaging for compensation of brain shifts. The result of this compromise is usually only a single imaging session at the end of surgery that may identify residual tumor for additional resection if needed. This compromise is now generally accepted as a standard feature of routine iMRI that in most cases involves only two imaging sessions, at the beginning and at the end of surgeries, instead of the originally used and more appropriate serial imaging. Updated navigation and the resulting sustained intraoperative accuracy became the casualties of improved image quality and resolution.

The other original source of the general idea of interventional and iMRI is the use of temperature-sensitive MRI to monitor and control thermal ablations of brain tumors and other diseases. This minimally invasive method has since become a major new direction in modern neurosurgery. MRI-guided interstitial laser surgery is now, 20 years after its introduction, available commercially and there are several successful clinical applications not only for malignant but also for benign brain tumors and for non-neoplastic diseases like epilepsy. MRI-guided Focused Ultrasound (FUS) is a noninvasive ablation method with the potential to change not only brain tumor surgery and functional neurosurgery, but also other related fields of clinical neurosciences. FUS does not use ionizing radiation, is repeatable, and can be monitored and controlled in real time unlike all currently practiced radiation therapy. Neuromodulation by FUS can have several applications in neurology and psychiatry; targeted drug delivery by FUS opening of the blood–brain barrier could be a real game changer in chemotherapy and in other branches of neuropharmacology. All of these currently discovered and far-reaching advances are the results of the introduction of MRI in neurosurgery and in therapy.

Early results from all the pioneers of iMRI demonstrated that this novel approach could improve the completeness of glioma resections and help to perform more extensive tumor removal without causing new neurological deficits. First, it was proven mostly for low-grade tumors that surgeries using iMRI could lengthen survival; later clear benefits were demonstrated for higher-grade tumors, too. Since then a substantial number of investigations indicate a clear benefit of gross total tumor resection on overall- and recurrence-free survival in patients with both low- and high-grade gliomas. These findings strongly motivate further advancing of the field. It was also demonstrated that in some benign tumor surgeries, like those for pituitary adenoma, iMRI might provide important imaging clues that can make the surgical interventions more complete, more successful and safer. IMRI was also introduced into endoscopic sinus surgeries with potential use in skull-base surgery.

The last 10 years have brought even more monumental changes. The introduction of MRI methods for depicting functional anatomy using advanced MRI techniques like functional MRI (fMRI) and Diffusion Tensor Imaging (DTI) were embraced not only by basic neuroscientists but also by some clinical neurosurgeons. Comprehensive imaging that integrates all the anatomical and functional information and relates these to the actual location of tumors can provide the surgeon with the wealth of information that was unavailable and unimaginable in traditional neurosurgery. These imaging data now can be used for surgical planning before and for guidance during surgery. This combination of preoperative and intraoperative imaging data can demonstrate a less well-known advantage of iMRI: helping to execute the preoperative surgical plan. Surgeons relying on the complex information provided by advance neuroimaging are able to remove more tumors and avoid complication after careful preoperative preparation and intraoperative presentation of the plan. Computerized image-processing methods like image fusion with nonrigid registration and more advanced navigation techniques can facilitate the process of intraoperative decision-making. Updated imaging can include intraoperative fiber tracking combined with electrophysiology in awake patients.

Intraoperative decision-making that requires the knowledge of tumor extent can be enhanced by intraoperative methods that may provide real-time biomarkers for tumor. Areas under investigation include mass spectrometry, Raman spectroscopy, and probes detecting radioactive molecular tumor detecting agents. These methods are potentially more sensitive and specific than MRI and can be localized and registered to the MR images. Using the combination of preoperative functional anatomical data, applying those for model generation for surgical planning, utilizing all features of intraoperative imaging and navigation and exploiting additional surgical decision-making tools, it is possible to further improve surgical outcomes for malignant brain tumor surgeries beyond the current results.

Proving efficacy, however, is challenging. Total resection of malignant brain tumors is an unworkable goal since in most cases tumor infiltrates normal brain and it is impossible to resect without causing new neurological deficits. Each individual case is different in the extent of tumor invasion and by location in relationship to functionally critical regions. Also, currently we have no optimal specific MRI method to distinguish edema from infiltrative tumor and the sensitivity of MRI is insufficient to produce an accurate map of tumor extent. The most significant for influencing efficacy and outcome among them is the mandate for the neurosurgeon to prevent new neurologic deficit as this impacts quality of life and has also been found to impact survival. Data supports that the greatest impact of iMRI on extent of resection is in tumors in noneloquent regions. The combination of tumor map and correctly registered fMRI-DTI data can provide an optimal surgical plan that can be correctly executed only by using iMRI by updating the anatomic image during surgery. However, if the definition of success is the removal of maximal amount of tumor without new functional defect, the definition of success and outcome is different and not based on survival alone.

iMRI has continued to improve glioma surgery but more exciting applications are ahead in other areas of neurosurgery. iMRI has been applied for vascular, spinal, and skull-base treatments, too. Most of these newer applications require advanced 3T MRI platforms for faster and more flexible image acquisitions than those available in the early stages. The full potential of iMRI can only be reached if advanced MRI is complemented with other imaging modalities in an intraoperative setting. For vascular interventions and surgeries X-ray fluoroscopy and angiography is necessary, for spine procedures MRI is extremely helpful but not without X-ray CT that provides details of the bone; similarly skull-base surgeries require both MRI and CT guidance. The potential advantages of molecular imaging are only conceivable if PET/CT or optical imaging is available in the surgical environment. Ultrasound can be an essential real-time monitoring device of brain shift, replacing the need for multiple serial MR images during surgeries. Development of an integrated navigational system based on the combination of US and MRI is necessary to manage the brain shift challenge that every neurosurgeon is faced with. This clinically well-justified solution also requires further improvement of multimodality nonlinear registration methods.

The Brigham and Women's Hospital Advanced Multimodality Image Guided Operating room (AMIGO) is the first implementation of this multimodality concept. MRI is the primary intraoperative imaging modality that can be supplemented with any other imaging method that is necessary for a given clinical procedure. AMIGO is a testbed not only for new neurosurgical procedures but also for other surgical and interventional applications. The success of iMRI in neurosurgery initiated and motivated the acceptance and use of intraoperative MR imaging and integrated navigational guidance in other fields. Neurosurgeons who pioneered stereotactic surgery, frameless navigation and iMRI have inspired their colleagues in other fields to embrace modern advanced image-guided surgical technologies in their particular fields. In AMIGO, which is a translational component of an active multidisciplinary program, the interaction and cross-fertilization between neurosurgical and other projects is an assurance for further progress of the entire image-guided therapy field.

Future improvements of iMRI may result not only from further progress of imaging technologies, but also from devices and tools that are guided by MRI. Among those are endoscopes, especially flexible neuroendoscopes, endovascular catheters and devices, and robotic surgical assistants. MRI tracking and MRI-based control of these devices may have a substantial role in the future of neurosurgery. It has been anticipated since the introduction of iMRI that new surgical approaches will be developed by innovative neurosurgeons equipped with iMRI technology. These developments continue to emerge. Further innovations will rest on the development of MRI-compatible devices like endoscopes, catheters, electrodes, and robots. Integration of the MR imaging methods with various therapy devices and robots can transform open neurosurgical procedures into minimally invasive image-guided surgeries by changing surgical techniques and approaches leading to new treatments for tumors, vascular abnormalities, and other diseases of the brain and spine.

In the last two decades, iMRI has been advancing and improving. It has moved through the stages of discovery, acceptance, and routine clinical use in neurosurgery and now it spreads into other surgical fields. It is still a not fully developed and mature technology, with presently only a limited number of clinical applications in which efficacy is already proven. Nevertheless, it is anticipated that, in combination with other advanced imaging, image processing and navigational technologies, and after integration with therapy delivery devices, its usefulness and effectiveness will be further verified. This book represents an important step in that direction.

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