

Development of Intraoperative MRI: A Personal Journey

Rudolf Fahlbusch

Abstract The initial attempts at intraoperative image guidance and imaging dates back to early 1980s. Since then Neuronavigation and intraoperative imaging technologies were developed in parallel. This work aims at summarizing the developments and giving an insider's view into the beginning stage of these technologies. The successes and obstacles encountered in the first few decades are relayed from the angle of one of the initial developers.

Keywords Intraoperative MR · MRI · Navigation

Dreams in my neurosurgical life were focussed on continuous improvement of surgical results and I was convinced that this could be achieved by early or real time testing. In the seventies I introduced endocrinological methods to predict early outcome of pituitary surgery. In the eighties neurophysiological monitoring for brainstem- and cerebellopontine angle (CPA) tumors improved functional surgical results. In the nineties computer – and engineering sciences were incorporated in surgical planning and surgical manoeuvres, in order to obtain a safer and more accurate brain tumor surgery. From the very beginning neuronavigation and intraoperative MRI were – from my point of view – two parallel developments, supporting each other. This shall be illustrated by my personal experience. Certainly this is not a systematic complete presentation of all efforts in this field.

There are moments for decisions in our professional lives, which can be regarded as destiny, maybe a favourable opportunity, prepared already in our inner development. Such an event happened to me in January 1992, when Peter Heilbrunn, at that time Chairman of the Department of Neurosurgery University of Utah in Salt Lake City, and main organiser of the Lende Winter Meeting, invited me to his winter house in Snowbird. When he asked Robert Spetzler and myself for a visit of his bedroom we could not

understand immediately, which machine Peter was going to introduce to us there. Some days later, in his computer-laboratory, which came out to be the first one in neurosurgery up to my knowledge, he presented to me the first prototype of a pointer related neuro-navigation system. When I asked him to provide me with the first commercial navigation system in Europe, this happened to us in Erlangen in 1993. Peter Heilbrunn's pilot-system ("machine vision") was later commercialized as the Stealth System by Surgical Navigation company, directed by Kurd Smith, who helped intensively and frequently to integrate the system in our OR. It was *Richard Buchholz* from St. Louis, who completed the device, introducing also special LEDS (This navigation system was distributed later by Sofamor-Danek and latest by Medtronic). It was at a much earlier opportunity in the middle of the seventies when I would have had the chance to realize the significance of an early mechanical navigation system, I overlooked it a long while, after its principles were presented to us by Eiju *Watanabe*, when he was a research fellow in Erlangen, coming from Tokyo University. Retrospectively I was not completely convinced about the practical use of this-at that time – not so accurate system. Nevertheless we used it for a while in traumatology cases. *Watanabe's* cooperation with his teacher Kintomo *Takakura* was published in 1987 [1]. Today he is regarded as the "father" of the modern neuro-navigator.

Other pioneers in this field of intraoperative imaging were Patrick Kelly with "volumetric stereotaxy" in 1979 [2], Schlöndorff, a German ENT-professor with "computer assisted surgery" in 1986 [3] and Alim-Louis Benabid, who constructed a stereotactic robot for performing biopsies and positioning of deep seated electrodes in 1987 [4]. Together with Christian Saint Rose he had also developed a neuronavigation system (see below). With the beginning of the nineties the former neurosurgeon and later radiologist Frank Jolesz founded together with the radiologist and computer scientist Ron Kikinis the first Surgical Planning Lab in Boston. In 1995 Kazuhiru Hongo introduced navigated micromanipulation onto the way of robotics. As early as

R. Fahlbusch
International Neuroscience Institute Hannover, Hannover, Germany
e-mail: fahlbusch@ini-hannover.de

1991 Dade Lundsford introduced intraoperative CT (ioCT) in Pittsburgh, but gave it up due to minor resolution for imaging of brain tumors.

The following experiences shall illustrate how close developments in neuronavigation and intraoperative MRI were running parallel and, supported each other. In the beginning of the nineties a technical engineer from Zeiss company, Mr Marcovic, stayed with us in our operating room in Erlangen as a guest (observer) After some days he asked me, how far I would be interested to see the MR-images no longer in the traditional way on the screen at the wall, but within the eyepieces of the microscope. I was fully convinced by this principle, when Mr. Marcovic and Mr. Lubner demonstrated me the first pilot microscope in the Zeiss laboratories later in Tuttlingen, which could offer projection of MR images into the eyepiece of the microscope for the use of navigation. Furthermore I could discover, that this Zeiss MKM was not only a tool for neuro-navigation, but offered also robotic potential. Its movement from the stand-by position to the point of view position in the operating field could be ordered by voice. In my eyes this was the birthday of microscope-guided navigation. So far we were working with pointer-guided systems for example with the Stealth navigation system. Some months later I visited the Siemens development laboratories in Erlangen and became aware of a newly developed open MRI. The 0.2 T machine offered not only an acceptable resolution for diagnosis, but could document manoeuvres in orthopaedic surgery, in a way of combined imaging and navigation, showing nearly on line movements of instruments.

It was during the Meeting of the “International Pituitary Neurosurgeons Society” in Bamberg, at the opportunity of a social evening event in a beer cellar, when I asked my colleagues, if they have heard also that someone in United States is going to introduce MRI in the operating room. I was so much surprised that my table neighbour Peter Black said, “Yes, it is me”.

It was only a question of time when I went to see the first equipment for ioMRI, the 0.5 T Signa SP (Double donut), in Boston. This was a development of GE in cooperation and on demand of Frank Jolesz and Peter Black, probably as a result of their experiences they had gained in their Surgical Navigation Planning Lab: the problem of brain shift. After an intensive preparation time of more then 2 years-including safety aspects for patients and medical staff being in or close to a magnetic field for a longer time- the first operation a brain biopsy was performed in June 1995-the first trepanation was performed in January 1996. Peter Black had invited me to demonstrate a biopsy for a brain tumor in fall 1995, I could observe ENT doctors using a copper-endoscope for surgery of the paranasal sinuses. It was obvious that this continuously running magnetic field tolerated within its field strength only MR compatible equipment, starting with surgical instruments ending with machines for anaesthesiol-

ogy, positioned close by. A narrow working area for the neurosurgeon was the price for receiving online MRI data. The neurosurgeons could use this permanent image information during their resection of a brain tumor, which allowed them to follow and compensate the brain shift for navigation for the first time. I was fascinated too by the Surgiscope, a highly sophisticated navigation system, developed originally by Alim-Louis Benabid and Christian Saint Rose, pioneers in neuronavigation, Saint Rose had demonstrated convincingly its accuracy to me during a resection of a pediatric glioma in Paris. Later it came out that Electa company, the distributor of the Surgiscope, and the distributor of the first open low field MRI (Magnetom) Siemens had no common “Schnittstelle” – this was for me the end of a potential realisation.

Our wish to realise an intraoperative MRI system together with navigation in Erlangen was favoured by the fact, that the former director of Siemens Medical Solution, Dr. Grassman became Director of Zeiss, Tuttlingen and that he was followed by Prof Reinhardt, with whom we cooperated before with some projects of MRI visualisation of pituitary tumors and surrounding arteries (MR angiography.)

One year after our common decision, induced by Mr Schöck, the chancellor of Erlangen University, our new OR suite with the 0.2 T open MRI and the Zeiss MKM (Figs. 1 and 2), could be realised together with the neurosurgeon Ralf Steinmeier. We were able to perform our first operation in March 1996-accompanied by a lot of worries. Would everything run really well during the transport of our patient with an open trepanation after a brain tumor resection from his position on the operating table, into the gantry of the MR scanner, then docking this table to the MR machine, which took this over as examination table-and the same procedure backwards? What about sterility during this prolonged surgery? How would the images look like, would the resolution of images be sufficient, how intensive would artefacts influence the results? For pituitary surgery



Fig. 1 The original, initial ioMRI (open Magnetom (version 1a) in Erlangen. *Above:* view from the room with the Magnetom Open into the OR room. *Below:* view from the OR with Zeiss MKM and Stealth station to the MRI room

Fig. 2 Docking manoeuvre of the OR table with the MR scanner (version 1a)



we learned to avoid drilling artefacts by using porcelain coated drills instead of stainless steel drills and to insert a small wax plate at the sellar floor after tumor resection to separate the intrasellar space from the sphenoid sinus, with its bleeding artefacts during data acquisition.

From the very beginning of developing intraoperative MRI there existed different options and concepts for its realisation, which could not be tested in an experimental way before:

A continuous magnetic field for on line imaging with surgery within the magnetic field.

A magnet separate from the operating field, where the advantages of microscope navigation could be used. Another concept decision was related to the field strength: low field vs high field: This concept as well as the concept of the relation of the patient's to the magnet position is till today in discussion: Shall the patient be transported into the gantry of the magnet or the magnet to the patient. We used pointer related navigation and microscope guided navigation as well. At the beginning it was necessary to have two different rooms, one room for the surgical procedure, including navigation and the other room for MR control. Both were connected to each other, but could be separated by a shielded door. This had the advantage that the MR room could be used during surgery also for examinations of other patients (a concept in ioMRI systems, which is still used today for commercial reasons.) At that time we could not perform surgery and MRI examinations in one common room. Tests have demonstrated that there was no compatibility of equipment. 1995 and 1996 in parallel the Heidelberg group of neurosurgeons (Stefan Kunze, Christian Wirtz, Volker Tronnier) had developed "our" concept too, they introduced



Fig. 3 ioMRI (version 1b) integration of the compatible navigation microscope Zeiss NC4 close to the modified diagnostic and therapeutic operation table

compatible coils as well as a special operating table. Where their operating room was large and the MRI room small it was the other way around in our concept. This was an unforeseen advantage, since we could work later on with the newly introduced Zeiss NC4 closer to the MR gantry, within the room with the Magnet, some tests have demonstrated before compatibility of the equipment (Fig. 3, version 1b). From now on we could operate on the diagnostic MRI table which was connected with a special compatible head holding device, the time for major transportation seemed to be passed away. We also found out that we could work without any compatibility problems outside and at the so called 5 Gauss line (Fig. 4).

Chronologically the introduction of a high field strength MRI, the 1.5 T (Philips) was just following the developments of low field MRI systems in Boston, Erlangen and Heidelberg

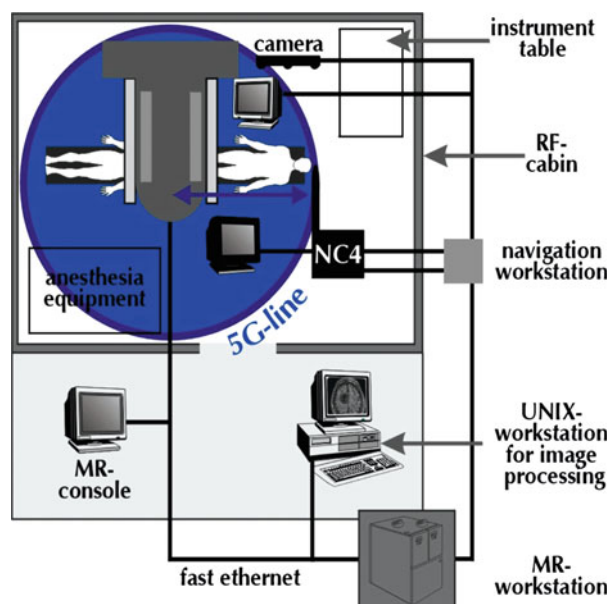


Fig. 4 Head position and surgery at the s.c 5 Gauss line, the safety border for safe surgery (version 1b)

of in 1997. The radiologist Charles Truwitt, together with the neurosurgeon Walter Hall gained their first experiences with biopsies, later with trepanations at the University of Minneapolis. However they were unable to introduce navigation at the beginning. Initially biopsies were taken close to the gantry of the MRI on the specially equipped diagnostic table, later on the trepanations had to be performed depart from the gantry and the table had to be transported some meters from a more distant place for surgery. In contrast to this concept of patient to the magnet Garnette Sutherland developed a system for magnet to the patient (1.5 T MRI, IMRIS) in Calgary, Canada in 1996.

In contrast to these efforts of early installation of high field magnets the development of low field system continued, stimulated by the attraction of lower costs and earlier availability. On one hand John Koivokangas installed an open 0.36 T MRI (Philips) in Oulu, Finland in 1996/1997, following the concept patient to the magnet. A similar device was introduced by Ronald E. Warnick and John Tew with the 0.3 T MRI, produced by Hitachi company and was later used by Kintomo Takakura and Tomokatsu Hori in Tokio. The first an ultra low field MRI system in a magnet to patient system was developed in Israel and introduced to patients by Moshe Hadani in Tel Aviv and by Peter Carmel and Michael Schulder in Newark: the Odin Pole Star N10 had a field strength of 0.12 T in 2000, the N15 version a field strength of 0.15 T. The transportable magnet is positioned below the operating, when not needed and can be swung upwards to the head, when intraoperative maneuvers shall be controlled. Till today the discussion about the value of a “useable resolution” of the low field images, stands in dis-

cussion with the more convincing images, gained by high field systems.

The real breakthrough in the use of intraoperative MRI happened from our point of view, when we were able to combine functional navigation with high field 1.5 T MRI in Erlangen (Fig. 5 and 6). After intensive planning and developments together with Christopher Nimsky and the industrial companies we could integrate the Siemens 1.5 T MRI Sonata and the BrainLab Vecor Vision sky system navigation (Vilsmaier, Ehrke, Kraft) in our new concept. This included also an integrated head coil for automatic registration intraoperatively. Functional MRI, using tools of MEG (Kober, Grummich) and the Bold effect of MRI (together with Oliver Ganslandt) allowed accurate localisation of eloquent areas such as sensor, motor, speech area (Broca and Wernicke). Functional and morphological data could be segmented, used for intraoperative navigation and could be upgraded after intraoperative MRI control. With the version of a rotating table the patient’s transport was solved, we could work at the 5 Gauss line with normal instrumentation. Even epilepsy surgery with EEG and ECG detections was successfully performed (Michael Buchfelder, Johann Romstöck). An experimental test documented that even the use of a robotic system close to the operating table was also tolerated. The advantages of high field strength for quicker acquisition time and improved anatomical, imaging became obvious: the intraoperative resolution quality was the same, even superior, to the preop one, we came to the statement that there is a necessity to incorporate functional imaging and visualisation into ORs, since about 30–40% of resectable brain tumors (pituitary adenomas and gliomas for example), are overlooked or not visible initially and can be resected safely, which can be documented immediately. The other high field strength advantages are functional imaging which allowed us also to complement cortical mapping with DTI-tractography (Christopher Nimsky) and to introduce Proton spectroscopy with Ganslandt and the physicists Moser and Stadlbauer from Vienna a potential for higher cytoreduction. Meanwhile it became obvious that there was no need for more than one, maximal three intraoperative MRI controls, which made the permanent online detecting of date unnecessary. The first ioMRI system, the double doughnut, was no longer promoted by its industrial company. With the availability of 3 T MRI for diagnostic purpose, with advantages for functional and metabolic imaging, there introduction in the OR was only a question of time. In 2005 and 2006 Necmettin Pamir (Siemens), Christian Raftopoulos (Philips) and Robert Spetzler (GE) started to install these systems for therapeutic use.

In 2007 we opened the INI-BRAIN SUITE at the International Neuroscience Institute: the first Open (70 cm bore!) intraoperative high field MRI for therapeutic use (Fig. 7). For the first time I was convinced to plan “2 operating

theatres in one room” simultaneously. The actual one for stable daily use on high quality level, the later one a 3 T, in case that the actual problems of 3 T MR will be solved: surface distortion, workflow with table transportation. Integration of ceiling mounted microscope Zeiss Pentero. Retrospectively the time from planning and decision for an MRI lasted 1 year for the 0.2 T version, nearly 3.5 year for the 1.5 T version in Erlangen and less then 2 year for the 1.5 T version in Hannover. The walls of the OR are isolated in a way required for 3 T systems. The exchange from a 1.5 T to a new 3 T (Siemens Verio) would prolong the 5 Gauss line only approximately 20 cm (4.5–4.2 m distance) from the Gantry.

It happened in October 2004 in Dresden, at the opportunity of a joint meeting of the German Society and German Academy with the American Academy of Neurosurgeons that the necessity of ioMRI was accepted obviously in the international neurosurgical community. This was the definite result of a contemporary formal discussion between Spetzler and Fahlbusch in the topic *Controversies in Neurosurgery*:

Intraoperative MRI: Gimmick or Godsend. Meanwhile about 150 ioMRI systems are installed world wide, dominated by low field systems. All systems have different advantages and disadvantages for:

1-image/quality benefit, 2-acquisition time, 3-imaging modalities workflow, and 4-costs

The scientific development of intraoperative imaging were accompanied by a number of meetings on local and international level. Since 1996/1997-on the US level – Peter Black and GE initiated symposia and workshops – with GE users as well as guests using other equipments – in Boston and at the opportunity of Congresses of AANS, CNS and WFNS. In Europe symposia were organised by René L. Bernays (the later first president of the Intraoperative Imaging Society in Foundation) in Zürich, Switzerland and by Johannes Schramm (the later EANS president) in Seeheim Jüenheim, Germany as an EANS Symposium. In Germany the first symposium for navigation and intraoperative MRI was organised by Joachim Gilsbach, Aachen, fol-

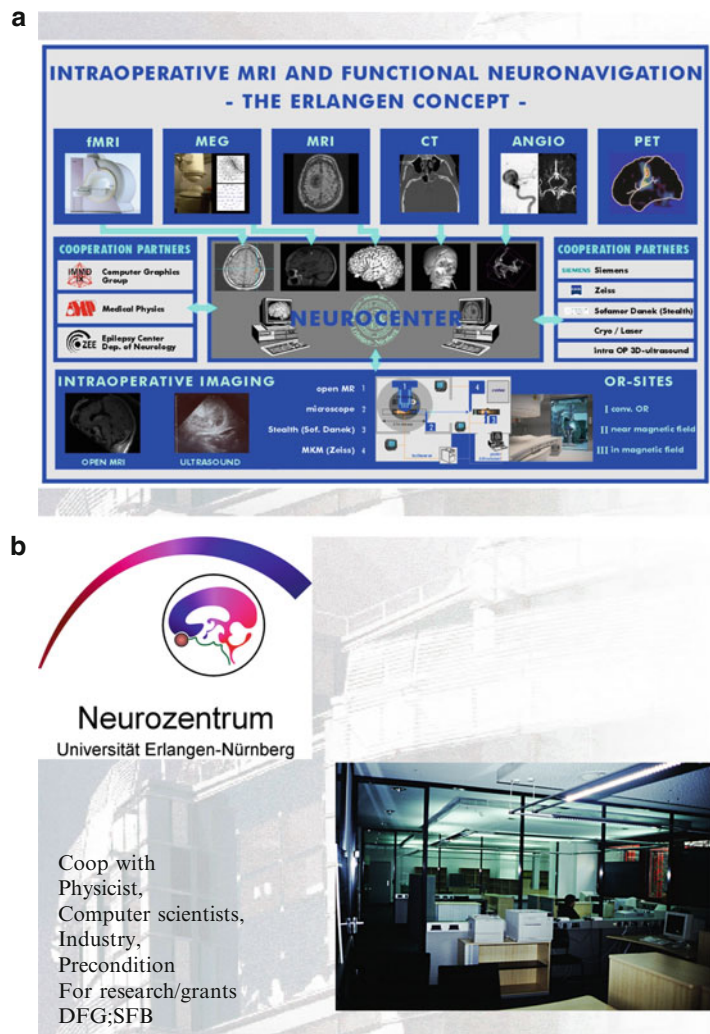


Fig. 5 (a) Concept of the interdisciplinary Neurocenter (1996) Intraoperative MRI and functional Neuronavigation – the Erlangen Concept – to centralise neurodata for fusion, post processing and finally surgery. (b) View into the interdisciplinary Neurocenter, opened 7/2000

Fig. 6 IoMRI version 2: 1.5 T MRI Siemens Sonata with a rotating table and the Zeiss NC4 (later Pentero) BrainLab Vector Sky Navigation system in one room. First operation in February 2002

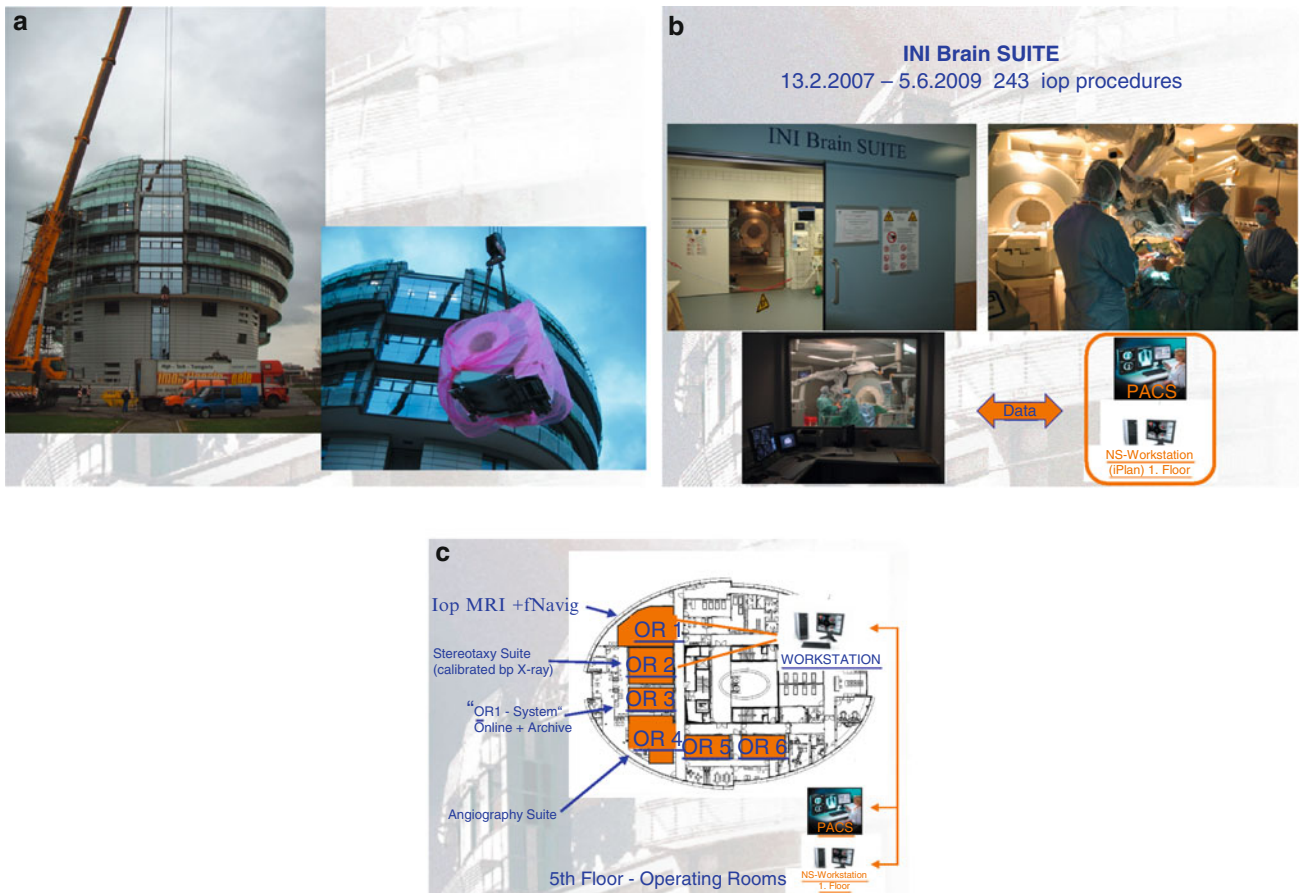
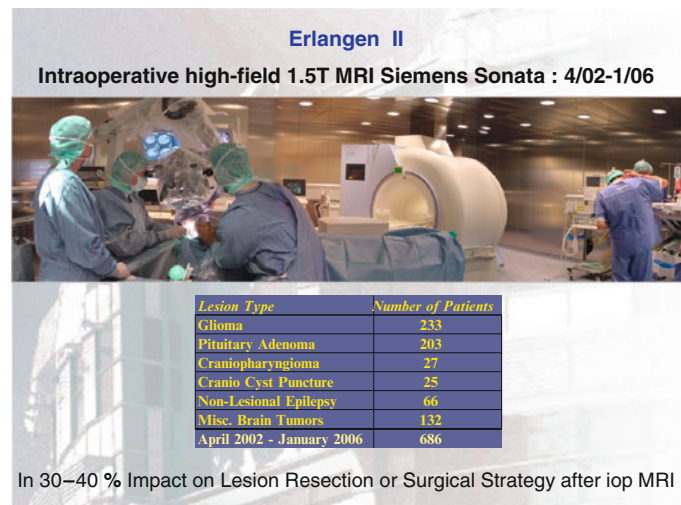


Fig. 7 (a) INI BrainSuite (version 3) Installation procedure of the MRI scanner at the INI Hannover. (b) View into INI BrainSuite. First operation 13.2.2007 Open 1.5 T MRI Siemens Espree with 70 cm Gantry with BrainLab Navigation and Zeiss NC4, later with a ceiling

mounted Pentero. (c) Localisation of the BrainSuite within the OR tract on fifth floor. Structural engineering for construction stability was planned already with the construction of the INI building, finished in 7/2000

lowed by Rudolf Fahlbusch and Christopher Nimsky in Erlangen, Maximillian Mehdorn and Arya Nabavi in Kiel. At this time it became obvious that neurosurgeons had to cooperate and incorporate with engineering and computer scientists. In 1996 we planned the “Neurocenter” in the Head. Clinic Erlangen, which we could open in July 2000, were experts and users of all clinical neurodisciplines and computer scientists gathered neurodata for post-processing procedures, which could be used for patients’ operation. (Led by the physicists Kober and Grummich, the computer scientist Hastreiter). Without this symbiotic input, research funding would not have been successful (Fig. 5a, b).

A round table with participants from clinical users such as neurosurgeons and radiologists, from industrial companies, university administration and ministries of the government was established to work out concepts for MEDICAL PROCESS OPTIMIZING, this included also economic aspects. Generally open problems in image guided surgery are the reduction and concentration of image data, application accuracy, visualization from 2D to 3D improved, as well as model based safety corridors for surgical maneuvers. Further perspectives for intraoperative MRI scanning are the following: less cost intensive systems should be provided, and improvement of ergonomic integration into the OR environment and workflow – a vision would be a nearly invisible and nearly online flat or tabletop magnet-integration of therapeutic devices (e.g. smart intelligent instruments, thermoablation, focused ultrasound).

Within the next 10 years we can expect the following developments in MR technology: “a widespread shift to higher field systems (3 T), further improvement of coil technology, including further increase of channels, introduction of molecular MRI agents and combined modality methods” [5].

Meanwhile hybrid systems for io-imaging are installed, respectively in development: Mitsumori Matsumae, Tokai university, Japan, connected the OR to a CT and MR suite as well [6]. In Boston the planned AMIGO suite will connect the OR with 3 T MRi and a PET-CT. Meanwhile a commercial PET-MR is available (Werner Siemens Foundation, Radiology Tübingen, Germany) and will open further aspects of application.

The escalating resources in intraoperative imaging include also other imaging developments, the already established ultrasound technology and the newly developing optical imaging, such as optical coherence tomography and multiphoton excitation microscopy-working on a cellular level, which for itself or in combination with ioMRI underline the scientific efforts, which will allow the increasing establishment of this kind of adaptive tumor resection as a standard procedure.

The First Society for Computer and Robotic Assisted Surgery was founded in Leipzig, Germany in 2001. It was expected that this scientific community would support further development. Later on members of industrial companies organised user meetings. BrainLab 1007 in Houston and 2008 in Singapore, whereas Medtronic organised a previous meeting for the foundation of the International Imaging Society in Lake Tahoe in 2008, under the guidance of Moshe Hadani, Rene Bernays and Michael Schulder. In June 11–14 2009 the *Intraoperative Imaging Society* was definitely founded in Istanbul, where Necmettin Pamir, one of the initial pioneers of intraoperative 3 T-MRI, hosted the first official conference of this society.

Conflict of interest statement We declare that we have no conflict of interest.

Acknowledgement I especially would like to thank Christopher Nimsky for his fundamental work in this field, he as well as other quoted authors are contributors of this book.

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<http://www.springer.com/978-3-211-99650-8>

Intraoperative Imaging

Pamir, M.N.; Seifert, V.; Kiris, T. (Eds.)

2011, X, 272 p., Hardcover

ISBN: 978-3-211-99650-8