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REVIEW

Intraoperative magnetic resonance imaging during surgery for pituitary adenomas: pros and cons

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Abstract Surgery for pituitary adenomas still remains a mainstay in their treatment, despite all advances in sophisticated medical treatments and radiotherapy. Total tumor excision is often attempted, but there are limitations in the intraoperative assessment of the radicalism of tumor resection by the neurosurgeon. Standard postoperative imaging is usually performed with a few months delay from the surgical intervention. The purpose of this report is to review briefly the facilities and kinds of intraoperative magnetic resonance imaging for all physician and surgeons involved in the management of pituitary adenomas on the basis of current literature. To date, there are several low- and high-field magnetic resonance imaging systems available for intraoperative use and depiction of the extent of tumor removal during surgery. Recovery of vision and the morphological result of surgery can be largely predicted from the intraoperative images. A variety of studies document that depiction of residual tumor allows targeted attack of the remnant and extent the resection. Intraoperative magnetic resonance imaging offers an immediate feedback to the surgeon and is a perfect quality control for pituitary surgery. It is also used as a basis of datasets for intraoperative navigation which is particularly useful in any kind of anatomical variations and repeat operations in which primary surgery has distorted the normal anatomy. However, setting up the technology is expensive and some systems even require extensive remodeling of the operation theatre. Intraoperative imaging prolongs the operation, but may also depict evolving problems, such as hematomas in the tumor cavity. There are several artifacts in intraoperative MR images possible that must be considered. The procedures are not associated with an increased complication rate.

Keywords Acromegaly · Intraoperative imaging · Magnetic resonance imaging · Neuronavigation · Pituitary adenomas

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Introduction

Intraoperative estimation of the radicality of tumor resection is made by the surgeon and depends on his ability to differentiate tissues and the complexity of the individual anatomy. When one concludes from the normalization of hormone secretion in active adenomas which are known to be very sensitive parameters, to date some 50–70 % of pituitary macroadenomas can be resected completely [1–3]. Particularly, in large adenomas, it is sometimes very difficult to assess whether total eradication of the whole tumor mass has been accomplished. Furthermore, many adenomas are not completely respectable even in very experienced hands for giant size, extremely asymmetrical growth and invasion. Transsphenoidal surgery became safer when Hardy [4] introduced the operating microscope for better visualization and fluoroscopy for orientation. The X-ray intensifier, which is still the most frequently used intraoperative imaging tool worldwide, however, allowed only the depiction of metal instruments against the skull base. There were humble attempts made to visualize the upper tumor surface with cisternography [5]. The evolution of pituitary surgery was paralleled by the improvement of intraoperative imaging [2, 6]. To date, several other intraoperative visualization tools are available: Okudera et al. [7] attempted intraoperative computerized tomography in 1993. However, use of radiation, fixed slice orientation, and

especially the poor soft-tissue contrast, compared with magnetic resonance imaging limited its application. Other attempts to localize the surrounding anatomical structures intraoperatively were the application of ultrasonography and the color Doppler system [8–10]. Preoperative datasets referenced to the patient's head via fiducials were traditionally used for intraoperative navigation and replaced, respectively supplemented fluoroscopy [11–16]. Datasets obtained from preoperative imaging are utilized for image guidance. When magnetic resonance imaging became available it was soon accepted as the standard diagnostic tool for pre- and postoperative imaging of pituitary tumors for its excellent soft-tissue contrast, its free orientation of slices and avoidance of ionizing radiation [17]. The concept of intraoperative magnetic resonance imaging to determine the amount of tissue resection already during surgery of brain tumors was born in 1994 in Boston [18–20].

Since then a growing numbers of departments all over the world have acquired MRI systems into their operating rooms. Several Departments of Neurosurgery have undergone evolutions and later upgraded a low intra- to a high-field MR-system [21–23] or a high-field into an ultra-high-field MR-system [24–27].

Since 2002, the authors have the possibility to use a 1.5 T Magnetom Sonata Maestro Class scanner (Siemens AG Medical Solutions) in a single room concept with a rotating surgical table [22, 28, 29]. They previously gained initial experience with a low-field system which was operative between 1996 and 2001 [21, 23, 30, 31]. To date, there are many different intraoperative MRI suites throughout the world installed and in use. The systems do not only differ in the strength of the magnet, which directly determines the quality of the images, but also in the constructional setup that is needed. The range of the strength of used magnet field lies between 0.12 and 3 T. Most intraoperative high-field MR-scanners to date are 1.5 T and magnetic fields lower than 0.5 T are usually referred as low-field systems.

Since estimation of the amount of tumor resection in pituitary macroadenomas by the surgeon is highly subjective, the gold standard to date is postoperative MR imaging. Interpretation of those images might be difficult with the development of postoperative artifacts resulting from the surgery. There is frequently a hematoma or packing material visible within the resection cavity a few days postoperatively that arise doubts as to how efficacious surgery was [32, 33]. Although the literature is a bit controversial [34, 35], most authors thus recommend delayed postoperative MRI a few months after the intervention, during which the artifacts are usually resorbed [2, 3, 17, 36, 37].

In non-functioning tumors, no biochemical parameters exist which could indicate persisting tumor. In secreting adenomas, a residual hormonal excess is generally accepted as the most sensitive parameter [38–40]. It has been questioned if a further MR followup is at all required if remission of oversecretion is achieved [17, 35, 37]. However, visible residual tumor necessarily means persistence of the endocrine disease [2]. Intraoperative depiction of this residual tumor offers the chance to extend tumor removal [41]. Most of the data to date available were obtained during transsphenoidal operations.

Patient positioning is crucial in the field of neurosurgery. Owing to the limit of the size of the bore of the MR scanner the semi-sitting positioning is not possible to use in pituitary surgery with intraoperative scanning. One has to take into account that an obese patient might fit in a MR scanner for diagnostic imaging, but does not, when positioned for surgery, draped and with the anesthetic lines and tube placed on the patient. The advantage of having the scanner in a different room might be the ability to use the scanner also for routine diagnostic imaging.

For imaging in transsphenoidal surgery, a flexible MR coil may be placed around the head so that the head can be moved during surgery without restrictions. Alternatively, the head can be fixated in a head holder with an integrated coil especially when a neuronavigation is needed.

Systems and setups

The first truly incorporated MR scanner within an operating theatre was built in 1994 by Black et al. [18] at the Brigham and Women's Hospital in Boston. It resembled a giant "Double Doughnut" (General Electric Medical Systems; 0.5 T). The surgeon stood between the two magnets and although real time imaging was possible a major limitation of the system was the narrow space offered for the surgical procedure. The Toronto Open Magnetic Resonance Imaging System looked almost identical, but had a sliding tray on which the patient was shifted between the giant vertical magnets [42].

A "twin-room-concept" was introduced in 1996 at the University Hospitals in Erlangen and Heidelberg, respectively, with an open intraoperative low-field MR scanner (Magnetom Open; Siemens AG Medical solutions, 0.2 T). The patients were transported on air cushioned trays so that technically unrestricted surgery could be performed in a standard shielded operating theatre. Mean scanning time was 15 min [23, 43]. The low-field images allowed to document the decompression of the optic chiasm and correlated reasonably with delayed postoperative standard 1.5 T MRI. For several patients, long-term followup data are to date available (Fig. 1). Nimsky et al. [21] implemented a navigation microscope within the fringe field of this MRI scanner so that the planning MR obtained in the anesthetized patient could be used to guide the surgical

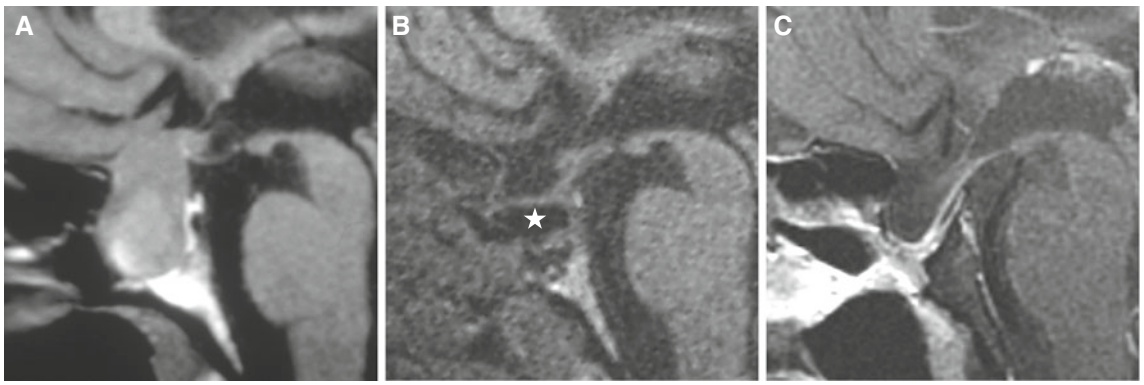

Fig. 1 Sagittal sections of preoperative 1.5 T (**a**) and intra- (**b**) operative low-field imaging (0.2 T) with some bone wax (*star*) at the level of the sellar floor after tumour resection in a 34-year-old woman with a non-functioning pituitary adenoma. The most recent followup study using standard high-field (1.5 T) imaging (**c**) documents, comparable to (**b**) the long-term result 10 years after the operation

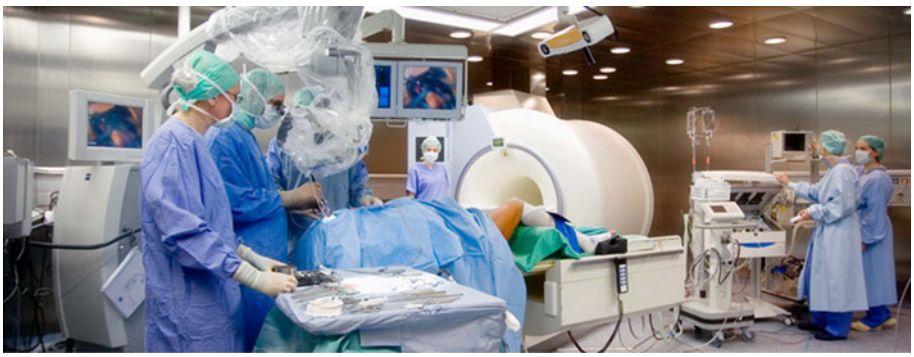

Fig. 2 The operation theatre at the Neurosurgical Department in Erlangen using an integrated 1.5 T Siemens Magnetom MRI as it is used for transsphenoidal surgery with the head of the patient positioned outside of the 5 G-line

procedure and even an update of navigation was possible utilizing intraoperative MRI data. A similar system with the same 0.2 T magnet, yet with a tiltable surgical table was described by Lewin et al. [44]. The mean time required for their imaging sessions was 15.4 min for the intraoperative and 11 min for postoperative imaging sessions. Likewise, Darakchiev et al. [45] used a standard 0.3 T magnet and a tilting table. Several authors described the use of the Pole Star N10 or N20 Medtronic system in which the navigation tools are integrated (0.12 and 0.15 T, respectively) for assessing the extent of pituitary tumors resection [46–55]. The ceiling-mounted, mobile 1.5 T IMRIS system installed in Calgary in 1997 moves the magnet over the head of the patient who remains stable [56]. A set of coronal and axial images added 20 to 30 min to the operative procedure. The setup used in Erlangen was described by Nimsky et al. 2004 [22]. The "Brain Suite" (Fig. 2) consists of a 1.5 T MR imager equipped with a rotating operating table and located in a radiofrequency shielded operating theater. A navigation microscope placed inside the 0.5 mT zone and used with a ceiling-mounted navigation system enables integrated microscope-based neuronavigation. In this system, the patient moves. Draping the patient and rotating the operating table for scanning takes some 2 min. The MR scanner can basically either be installed within the operation room or in a room next to the theatre ("twin room concept"). In the first setup, the use of normal surgical instruments is possible when the surgical field is outside of the 5 G line. The improvements in workflow, image quality, and efficiency between the low- and high-field systems in the same department were analyzed by Nimsky et al. [21]. More recently, 3 T systems were installed in a few centers [24, 26, 27, 57]. Even the higher field strength magnets required substantial modification of existing operating rooms.

The number of acquired images depends on the information needed for surgery. T1- and T2-weighted images can be used to determine tumor extension. Unfortunately, T1 without contrast does not depict differences between normal pituitary gland and residual tumor. Therefore, contrast is applied in most of these patients when T1 images are acquired. T2-sequences on the other hand have proven to be the most accurate and the fast acquired images to identify not only all anatomical landmarks, critical structures, or cystic components but also to differentiate residual tumor from hematoma within the resection cavity. Before surgery, usually sagittal and coronal images are acquired ideally in thin slices through the whole tumor.

A comparable dataset is usually obtained intraoperatively when the surgeon feels that he has resected all the tumors or achieved his best if total resection is not feasible. For minimizing the artifacts on the images, heamostasis has to be achieved and as little material as possible left in the situs.

Visualization of residual tumor, unfortunately, cannot be equated with resectability and that is a major limitation of the system. Whenever a residual tumor is suspected, however, the area can be checked again at the same procedure.

Results of low-field studies

In 1998, Steinmeier et al. [23] first published a series of 18 transsphenoidal resections of 15 non-functioning pituitary adenomas and three craniopharyngiomas with intraoperative low-field (0.2 T) MR scanning. In this series, they were able to extend the resection to a complete resection in three of six patients in whom residual tumor was identified. Fahlbusch et al. [30] showed that intraoperative low-field images compared favorable to delayed postoperative standard imaging. They point out that interpretation of intraoperative images requires additional expertise and resected additional tumor in 34 % of their 44 patients, which increased the rate of total removal from 43 to 70 % of their patients. Moreover, they defined predilection sites for residual tumor. Gerlach et al. [53] also compared the intraoperative images with standard postoperative images 3 months after surgery. They increased the total resection rate in their series by 38 % based on the assessment of intraoperative low-field images. A critical image analysis comparing intraoperative imaging with delayed postoperative routine 1.5 T MRI, however, decreased the number of total resections to 12 of 40, indicating that in low-field images small tumor residuals might not necessarily be properly depicted by the low-field MR systems.

Ahn et al. [46] first separated their 63 cases into two different groups. In 51 cases, a complete transsphenoidal resection seemed to be possible, whereas 12 showed a broad invasion so that a complete resection was not possible. Their results showed that even in the group of complete respectable tumors, the intraoperative MRI depicted residual tumor in 25 %. They were able to increase the complete resection rate from 75 to 94 % and used Gadolinium-coated paddies to better delineate the resection cavity.

Wu et al. [55] compared intraoperative images to standard postoperative high field 1.5 T MRI obtained within 72 h postoperatively. They revealed more residual tumor in the higher Hardy classification groups. Again, intraoperative imaging led to an increase of the overall complete resection rate from 42 to 84 %.

Bellut et al. [49] not only compared intraoperative with standard postoperative images but also biochemical remission in acromegaly to the intraoperative MRI. Again, the complete resection rate dropped from 38 to 32 of 39 when postoperative images where critically analyzed. Baumann et al. [48] attacked five giant adenomas and resected three of these. Whereas most of the literature is microsurgery based, Anand et al. [47] used only the endoscope as a visualization tool in their patients. They describe the low resolution and the limited field of view as disadvantages of the low-field system.

Low-field intraoperative MRI is able to reliably detect if a decompression of the visual pathways has been achieved. Recovery of visual function was in several studies correlated to the space created [51, 54, 58] between the upper tumor surface and the lower margins of the chiasm. Intraoperative imaging immediately after tumor resection appears to be less prone to artifacts, such as space occupying lesions which are seen on imaging a few days after surgery. If there is hematoma depicted, it can be verified and evacuated during the ongoing surgical procedure. A summary of currently published results with pituitary tumors and intraoperative low-field MRI is provided in Table 1 [1, 16, 23, 30, 46, 48–50, 53, 55, 59–62]. In all series, intraoperative imaging led to further resection of residual tumor in a substantial proportion of patients and an increase in the overall complete resection rate. Most authors point out that the weakness of low-field systems is the poor depiction of parasellar structures and small tumors. In all published studies, no higher complication rate has been reported due to the longer deration of the operation.

Less benefit resulted from low-field imaging also in craniopharyngiomas, where a substantial proportion of the operations were transcranial procedures [31].

Results of high-field studies

Dort et al. [63] published a small series of 15 patients with pituitary macroadenomas and intraoperative high-field MR-imaging already in 2001. Comparable to the low-field-series, the intraoperative MR depicted some residual tumor in 60 % of all cases and led to a further resection in 8 of those. Finally, the complete resection rate increased from 40 to 93 %. Fahlbusch et al. [28] described 23 selected patients with acromegaly in which complete resection of the adenoma, as determined by intraoperative MRI, increased from 56 to 77 %. However, they point out that biochemical parameters are more sensitive than MRI. Remission of growth hormone and IGF-1 secretion was only achieved in 44 % of those 18 patients in whom the tumor was completely resected. Of course, none of the patients in whom

Table 1 Results of intraoperative low-field imaging (0.12–0.5 T) on extent of pituitary adenoma resection; review of literature

Author	Year	Scanner used	Patients and adenomas	Suspected residual tumor on intraop.MRI	Eligible for further resection	Complete resection on further MRI	Complete resection at end of procedure	Intraoperative MRI lead to further tumor resection
Steinmeier et al. [23] (Erlangen)	1998	Siemens Magnetom open 0.2 T	$n = 16$ Macroadenomas	6 of 16 (38 %)	5 of 6	3 of 5	10 + 3 of 16 (81 %)	5 of 16 (31 %)
Martin et al. [59] (Boston)	1999	General Electric Signa SP open configuration 0.5 T	$n = 5$ Macroadenomas	MRI were performed at several stages of the procedure			3 of 5 (60 %)	–
Bohinski et al. [1] (Cincinetti)	2001	Hitachi AIRIS II vertical-field open magnet 0.3 T	$n = 29$ Macroadenomas	19 of 29 (66 %)	All 19	6 of 19	10 + 6 of 29 (55 %)	19 of 29 (65 %)
Fahlbusch et al. [30] (Erlangen)	2001	Siemens Magnetom open 0.2 T	$n = 44$ Macroadenomas	25 of 44 (57 %)	15 of 25	12 of 15	19 + 12 of 44 (70 %)	25 of 44 (57 %)
Walker et al. [16] (Boston)	2002	General Electric Signa SP open configuration 0.5 T	$n = 23$ 4 Micro- and 19 macroadenomas	13 of 19 Macroadenomas (68 %)	All 13	7 of 13 Macroadenomas	4 Microadenomas (100 %) 6 + 7 of 19 Macroadenomas (68 %)	13 of 23 (57 %)
Schwartz et al. [60] (New York)	2006	Polestar N-10 0.12 T	$n = 15$ Macroadenomas	3 of 15 (20 %)	All 3	3 of 3	12 + 3 of 15 (100 %)	3 of 15 (20 %)
Ahn et al. [46] (Seoul)	2008	Polestar N-20 0.15 T	$n = 63$ Macroadenomas Intended complete: $n = 51$ Intended incomplete: $n = 12$	Intended complete: 13 of 51 (25 %)	Intended complete: All 13 Intended incomplete: 6 of 12	10 of 13	38 + 10 of 51 (94 %)	19 of 63 (30 %)
Gerlach et al. [53] (Frankfurt)	2008	Polestar N-20 0.15 T	$n = 40$ Macroadenomas	26 of 40 (65 %)	7 of 26	1 of 7	14 + 1 of 40 (38 %)	7 of 40 (18 %)

Table 1 continued

Author	Year	Scanner used	Patients and adenomas	Suspected residual tumor on intraop.MRI	Eligible for further resection	Complete resection on further MRI	Complete resection at end of procedure	Intraoperative MRI lead to further tumor resection
Wu et al. [55]. (Shanghai)	2009	Polestar N-20 0.15 T	$n = 55$ Macroadenomas Hardy °II: 26 Hardy °III: 20 Hardy °IV: 9	$n = 23$ of 55 (42 %) Hardy °II: 5/26 (19 %) Hardy °III: 9/20 (45 %) Hardy °IV: 9/9 (100 %)	23 of 55	14 of 23 Hardy °II: 4/5 Hardy °III: 6/9 Hardy °IV: 4/9	32 + 14 of 55 (84 %) Hardy °II: 25/26 (96 %) Hardy °III: 17/20 (85 %) Hardy °IV: 4/9 (44 %)	23 of 55 (42 %)
Baumann et al. [48] (St. Gallen)	2010	Polestar N-20 0.15 T	$n = 6$ Giant adenomas	MRI were performed at several stages of the procedure			3 of 5 (60 %)	–
Bellut et al. [49] (Zürich)	2010	Polestar N-20 0.15 T	$n = 37$ Micro- and macroadenomas with Acromegaly (39 operations)	8 of 39 (21 %)	All 8	7 of 8	38 of 39 (97 %)	8 of 39 (21 %)
Theodosopoulos et al. [61] (Cincinetti)	2010	Hitachi AIRIS II vertical-field open magnet 0.3 T	$n = 27$ Macroadenomas	9 of 27 (33 %)	4 of 9	1 of 4	18 + 1 of 27 (70 %)	4 of 27 (15 %)
Vitaz et al. [62] (Louisville)	2011	General Electric Signa SP open configuration 0.5 T	$n = 100$ 9 Mircoradenomas 81 Macroadenomas 10 Other	–	–	–	76 of 100 (76 %)	–
Berkmann et al. [50] (Aarau)	2012	Polestar N-20 0.15 T	$n = 60$ Macoradenomas	23 of 60 (38 %)	20 of 23	13 of 20	37 + 13 of 60 (83 %)	20 of 60 (33 %)

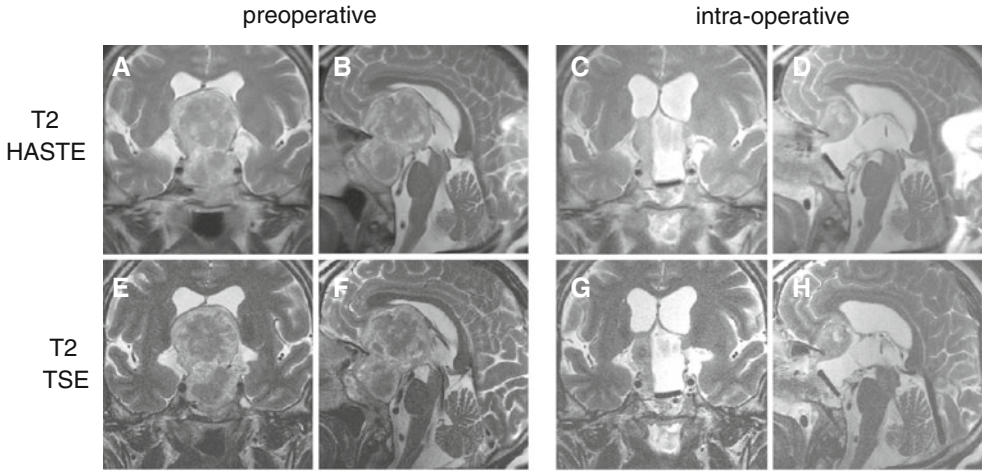

Fig. 3 The different image quality of perioperative T2-weighted HASTE-sequences (*upper row*; acquisition time ~25 s each) in comparison to T2-weighted TSE-sequences (*lower row*: acquisition time ~3:50 min each) pre- (ABEF) and intraoperatively (CDGH) showing some residual subfrontal tumour in a 56-year-old patient with a non-functioning "giant" pituitary adenoma

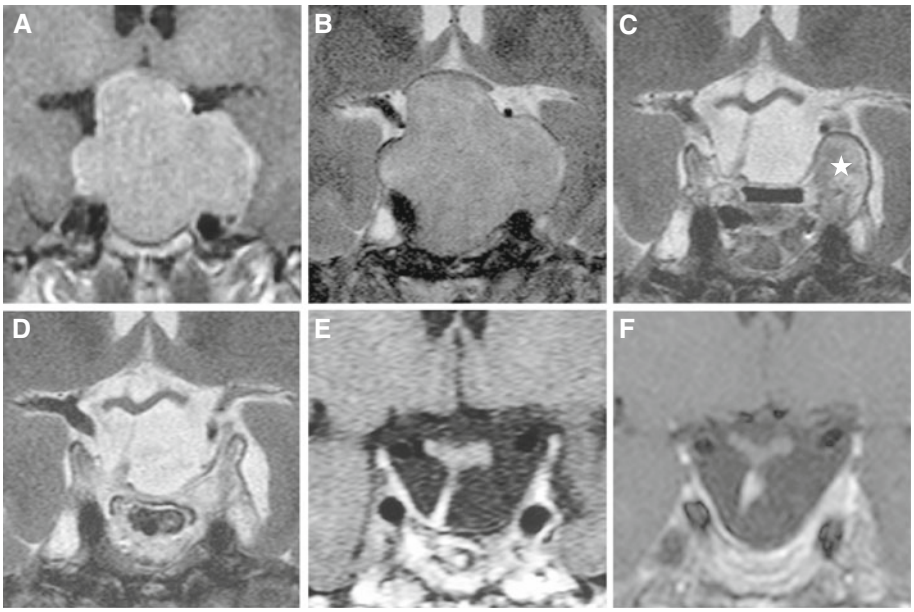

Fig. 4 A large intra-, supra- and parasellar pituitary macroadenoma in preoperative (**a**) T1-weighted and (**b**) T2-weighted TSE MRI in a 39-year-old patient. (**c**) shows the first intraoperative image (1.5 T T2 TSE) with some (*star*) residual tumour, which is further resected (**d**). Delayed postoperative images were obtained 3 months (**e**) and 5 years (**f**) after transphenoidal surgery. They reveal almost an identical result as the last post-resection intraoperative image (**d**)

residual tumor was visible achieved remission. The largest series so far published in 2006 derives also from the Erlangen group [29] and presented 129 non-functioning pituitary macroadenomas. Of these tumors, 103 seemed completely respectable. Intraoperative imaging led to a further tumor removal in 28 cases. The rate of complete resections rose from 66 to 90 % in this material, in which the decision to operate the patient with intraoperative imaging already represented a negative selection [29]. Only a minority of the large tumors was operated upon in the MRI suite, namely those with tumors of lesser likely hood of total resection. Microadenomas, in which the surgical success rate is high, were also excluded from most MR series.

The quality of images depends on the sequences used for image acquisition. Some information is gained already after less than a minute, while a higher resolution requires a longer scanning time and causes more delay with the procedure (Fig. 3). The major advantage of higher field strength is that also the parasellar space can be assessed. Thus, residual tumor, once detected, can be attacked in a targeted fashion and be reduced in its magnitude. In selected exemplary patients, such a more radical resection has been shown to be associated with a favorable long-term outcome (Fig. 4).

Similarly, Meng et al. [64] increased their total resection rate in the Bejing series. There are several reports already available with 3 T MR scanners, which document an

Table 2 Results of intraoperative high-field imaging (1.5–3 T) on extent of pituitary adenoma resection; review of literature

Author	Year	Scanner used	Patients and adenomas	Suspected residual tumor on intraop.MRI	Eligible for further resection	Complete resection on further MRI	Complete resection at end of procedure	Intraoperative MRI lead to further tumor resection
Dort et al. [63] (Calgary)	2001	Magnex Scientific IMRIS 1.5 T	$n = 15$ Macroadenoma	9 of 15 (60 %)	All 9	8 of 9	6 + 8 of 15 (93 %)	9 of 15 (60 %)
Hall et al. [57] (Minnesota)	2005	Philips Gyroscan ACS-NT 1.5 T	$n = 77$ Macoradenomas	n.s.	n.s.	n.s	n.s.	n.s.
Fahlbusch et al. [28] (Erlangen)	2005	Siemens Magnetom Sonata Maestro 1.5 T	$n = 23$ Macroadenomas with acromegaly Intended complete: $n = 18$ Intended incomplete: $n = 5$	Intended complete: 8 of 18 (44 %)	Intended complete: 5 of 8	Intended complete: 4 of 5	10 + 4 of 18 (77 %) Biochemical remisson: 6 + 2 of 18 (44 %)	5 of 23 (21 %)
Nimsky et al. [29] (Erlangen)	2006	Siemens Magnetom Sonata Maestro 1.5 T	$n = 129$ Macroadenomas Intended complete: $n = 103$ Intended incomplete: $n = 26$	Intended complete: 35 of 103 (34 %)	Intended complete: All 35 Intended incomplete: 12 of 26	Intended complete: 28 of 35	65 + 28 of 103 (90 %)	35 + 12 of 129 (36 %)
Jankovski et al. [25] (Brussels)	2008	Phlips Achieve 3 T	$n = 3$ Macoradenomas	1 of 3 (33 %)	–	–	2 of 3 (67 %)	–
Pamir et al. [27]. (Istanbul)	2011	Siemens Magnetom Trio 3 T	$n = 42$ Macoradenomas Intended complete: $n = 29$ Intended incompete: $n = 13$	Intended complete: 9 of 29 (31 %)	Intended complete: 7 of 9 Intended incomplete: 3 of 13	Intended complete: 4 of 7	20 + 4 of 29 (82 %)	10 of 42 (24 %)
Meng et al. [64]. (Bejing)	2011	1.5 T	$n = 30$ Macoradenomas	12 of 30 (40 %)	10 of 12	8 of 10	18 + 8 of 30 (87 %)	12 of 30 (40 %)

Table 2 continued

Author	Year	Scanner used	Patients and adenomas	Suspected residual tumor on intraop.MRI	Eligible for further resection	Complete resection on further MRI	Complete resection at end of procedure	Intraoperative MRI lead to further tumor resection
Lang et al. [26] (Calgary)	2011	Siemens Magnetom Verio IMRIS 3 T	$n = 9$ Macoradenomas	1 of 9 (11 %)	1 of 1	1 of 1	8 + 1 of 9 (100 %)	1 of 9 (11 %)
Netuka et al. [63]. (Prague)	2011	Signa HDx General Electric 3 T	$n = 86$ (incl 10 microadenomas) Intended complete: $n = 49$ Intended incomplete: n = 37	Intended complete: 15 of 49 (31 %)	Intended complete: 13 of 15 Intended incomplete: 18 of 37	Intended complete: 11 of 13	34 + 11 of 49 (92 %)	21 of 86 (24 %)
Szerlip et al. [67] (New York)	2011	Siemens Magnetom Espree 1.5 T	$n = 53$ (49 Macoradenomas) Intended complete: $n = 49$ Intended incomplete: $n = 4$	Intended complete: 29 of 49 (59 %)	Intended complete: 28 of 29 Intended incomplete: $n = 0$	Intended complete: 13 of 29	20 + 13 of 49 (67 %)	29 of 53 (55 %)

Fig. 5 Patient positioning with the head fixed in a head coil for intraoperative image acquisition and neuronavigation planning

increase of total resection of pituitary adenomas ranging from 11 [26] to 31 % [27, 65]. A summary of currently published results with pituitary tumors and intraoperative high-field MRI is provided in Table 2 [25–29, 63–67].

Combination with navigation

The availability of intraoperative imaging does not automatically imply that neuronavigation is always required. Intraoperative imaging can also be used for navigation. In the presence of a normal anatomy, the well-known anatomical landmarks like the vomer or the ostium of the sphenoid sinus might be sufficient to target the microsurgical approach to the sella even without intraoperative fluoroscopy. Endoscopic surgeons usually do not use any fluoroscopy for routine cases.

But, whenever the normal anatomy is lost to due to prior surgical interventions or in patients with poor pneumatization of the sphenoid sinus one may appreciate by neuronavigation. Furthermore, it can be used for teaching or training the transsphenoidal approach. The head of the patient must be fixed. In an intraoperative MRI unit, the referencing system can be integrated within the head coil (Fig. 5) or fiducials may be put on the patients head prior to image acquisition. It depends on the surgeon's choice which structures he finds useful for navigation. Some like to have just the ideal trajectory to the tumor where others prefer to also visualize tumor margins and the carotid arteries. The outline of the structures can today be superimposed into the microscopical view of the operative field (Fig. 6). The technique undoubtedly increases the comfort of the surgeon. Especially, in re-do surgeries with distorted anatomy or dense packing of the sphenoid sinus with various materials, neuronavigation helps us to identify the sellar floor and to extend bone resection [14]. However, utmost precision is required since misleading guidance might lead to a disaster. The endoscope itself can be integrated into the neuronavigation system for orientation within the sphenoid sinus or during the approach itself.

Intraoperative imaging versus endoscopic technique

Owing to the high costs of intraoperative MR scanners, only limited centers had the possibility to compare their results of endoscopically performed transsphenoidal surgery with those of an intraoperative MR imaging. Therefore, the important question whether the MR is superior to the endoscope or vice versa either to proof a gross total

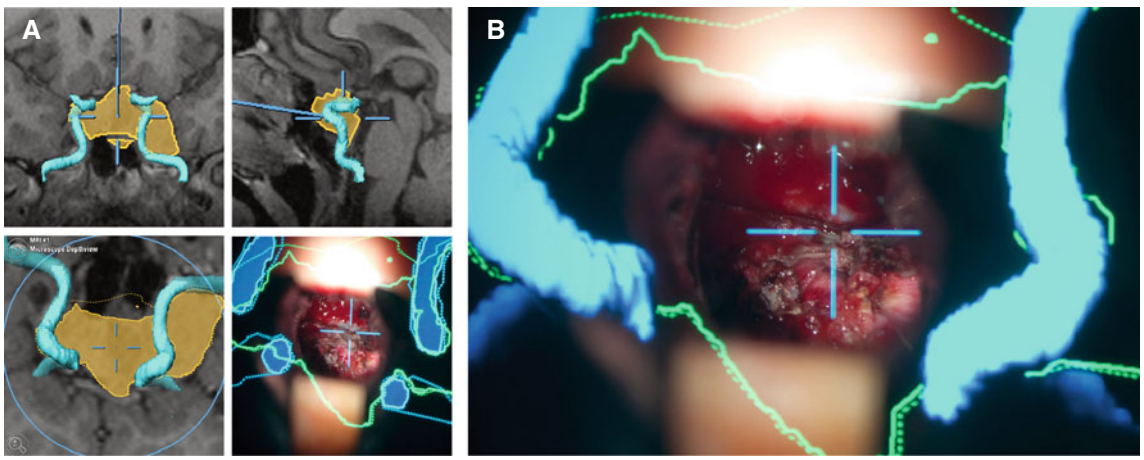

Fig. 6 Recurrent non-functioning pituitary adenoma in a 48-year-old female patient with broad invasion of the cavernous sinus. The 3D dataset of the intraoperative navigation planning MRI (**a**) provides crucial information to the surgeon, such as tumour volume (*yellow*), which can be manually segmented and visualized. (**b**) depicts the view of the surgeon through the microscope with the superimposed structures of the carotid arteries (*blue*) and tumor confines (*green*)

resection or to determine the amount of a residual tumor can presently not be answered.

Theodosopoulos et al. [61] used a 4-hand, fully endoscopic, transsphenoidal approach and compared the endoscopically determined results with an intraoperative low-field 0.3 T MR image. In their series in three out of 27 patients surgery was continued when residual tumor was identified on the intraoperative imaging which has not been visualized with the endoscope. Jane and Laws [68] comment that endoscopy accurately predicted residual tumor in 55 %, but incorrectly predicted gross total resection in 18 % of the cases. Especially, intrasellar tumor remnants may appear like normal gland especially in firm tumors and are consequently not resected although visualized by the surgeon. Schwartz et al. [60] also used a fully endoscopic, transsphenoidal approach when they presented their series of 15 patients in an ultra-low-field 0.12 T MR. In three cases, intraoperative imaging depicted some residual, suprasellar tumor that was further resected. Unfortunately, in four cases, intraoperative images mimicked normal "postoperative changes" (i.e., blood) as a residual tumor that was not visible during re-exploration, indicating that the low-field imaging technique has some drawbacks. Netuka et al. [65] also used an endoscopic approach in their series of 86 transsphenoidal operations of pituitary adenomas with intraoperative MR imaging. In 24 % of all cases, the operation was continued after MR imaging and increased the rate of gross total resection from 69 % to 92 %. Unfortunately, their series was not set up as a prospective study, but it is still the most important expert study to compare high-field MR imaging (3.0 T) with the endoscopic technique.

Intraoperative MR imaging and the endoscope find their limits in vascularized tumors, which lead to poorly visualized operation fields and hematomas that produced imaging artifacts.

Conclusions

Intraoperative MR imaging during surgery for pituitary adenomas to date is an established procedure. There is a huge variety of low and high-field systems available. High-field systems require enormous investments since the construction of the operating theatre and shielding need to be appropriate. They provide a higher resolution of images within a shorter data acquisition time. Almost all reported series demonstrate a higher rate of total tumor resection and higher amount of resected tumor in adenomas which cannot be totally excised. Low-field systems are cheaper, can be integrated into an existing operation room more easily, and also allow to estimate the radicality of surgery better than the subjective impression of the surgeon. Almost all systems provide an opportunity to navigate procedures on the basis of an MRI dataset that is acquired in the already anaesthetized patient.

Conflicts of interest The authors declare that they have no conflict of interest.

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