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The Significance of Intraoperative Magnetic Resonance Imaging in Resection of Skull Base Chordomas

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■ BACKGROUND: **Skull base chordoma can be a challenging surgical entity because of its invasive nature.**

■ OBJECTIVE: **In this study, the role of intraoperative magnetic resonance imaging (iMRI) to optimize the resection of skull base chordomas is evaluated.**

■ METHODS: **We performed a retrospective analysis of operated patients with skull base chordomas in the setting of iMRI. The clinical records, operative notes, radiologic images, tumor volumetry, location of the residual tumor, and surgical outcome were evaluated.**

■ RESULTS: **Fifteen patients were operated on for resection of skull base chordomas between 2010 and 2017 in our institution. Gross total resection was planned and achieved in 8 patients and partial resection in 7 patients. In 8 patients (53.3%), the preoperatively planned volume of resection was achieved and confirmed in the first iMRI control. In 7 patients, repeated iMRI controls were required to achieve the surgical target. In 3 patients, the tumor residual requiring further resection was located in the clivus and in 4 patients in the intradural space. The improvement of the preoperative deficits showed a significant statistical association with the resection of the intradural component and decompression of the brainstem.**

■ CONCLUSIONS: **This study shows that iMRI is a safe method for intraoperative assessment of the degree of resection and the volume and location of residual tumor when resecting skull base chordomas. When gross total resection of the tumor is not feasible, iMRI can be a useful tool for targeted tumor resection.**

INTRODUCTION

The significance of intraoperative magnetic resonance imaging (iMRI), stand-alone or in combination with an operative endoscope, has been widely accepted for maximal resection of invasive pituitary adenomas to improve the rate of gross total removal, to detect tumor remnant, and to improve progression-free survival.[1-10] A similar concept could be applied to resection of other skull base lesions, particularly invasive lesions such as chordomas.

Chordomas are rare tumors originating from remnants of the primitive notochord and predominantly located in the sacrococcygeal region and the clivus. They have an incidence of 0.08 per 100,000, and constitute 0.1%–0.2% of all primary intracranial neoplasms. Approximately 35% of chordomas occur in the spheno-occipital region and mostly involve the clivus, petrous apex, cavernous sinus, foramen magnum, and sphenoethmoidal areas.[11-13] Cranial base chordomas usually appear as encapsulated tumors, but they infiltrate the bone, along with the lines of least resistance.[14-18] Chordomas may also penetrate the dura and encase cranial nerves and neurovascular structures and compress various central nervous system structures such as the brainstem.

Maximal resection followed by adjuvant radiation therapy for residual or recurrent tumor is recommended. However, there are no standardized guidelines because of the rarity of the disease and the small patient populations in individual studies.[17,19-25] Nevertheless, patients with complete resection of the tumor have prolonged disease-free survival and overall survival.[11-13,17]

Key words
- Chordoma
- Intraoperative magnetic resonance imaging
- Outcome
- Skull base

Abbreviations and Acronyms
iCT: Intraoperative computed tomography
iMRI: Intraoperative magnetic resonance imaging
MRI: Magnetic resonance imaging
SD: Standard deviation

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Furthermore, chordomas show a tendency to recur and variable degrees of radioresistence.[22,24-34]

For resection of skull base chordoma, the surgeon depends on fixed anatomic landmarks for orientation and estimation of the degree of resection and the adequacy of neural decompression.[14,15] However, chordomas tend to invade multiple skull base compartments and to destroy the bony skull base and thereby surgically relevant anatomic landmarks. Because of the complexity of the tumor extension, surgical resection may be challenging despite diverse technical improvements and refinements of different approaches.[35-42] With conventional surgical techniques, the surgeon may miss a tumor residual, especially in complex and invasive lesions like invasive pituitary adenoma.[3,7,10] Direct visual assessment may not be sufficient even using the operative endoscope to confirm completeness of the resection or to estimate the volume of the residual tumor.

Some studies have described using iMRI for resection of skull base tumors[43-45]; however, there is no analysis of the value of iMRI in resection of skull base chordoma, which was sporadically mentioned as a small subgroup in previous reports.[44] In this article, we present our experience with 15 patients with skull base chordomas, which is the first case series of skull base chordomas operated on under iMRI control reported in the English literature. The usefulness of iMRI in achieving the goal of surgery is discussed. The functional outcome is also reported and analyzed.

METHODS

The study was approved by our ethical committee. Using iMRI was approved by the local ethical committee and all patients were informed about the technique and gave their signed concent to iMRI during tumor resection and to the data being used for research purpose.

Study Design. The study was a retrospective case series.

Participants and Study Size. We performed a retrospective analysis of patients operated on for resection of skull base chordomas under iMRI control from March 2007 to August 2017.

Data Source. The sources of data were admission and discharge notes, hospital course note, preoperative radiology, iMRI, operative notes, and follow-up MRI.

Settings and Variables. The patient population, preoperative clinical features, preoperative clinical status, radiologic images, tumor extension and volume, surgical approaches, operative reports, intraoperative images, site of the residual that required further resection, preoperative and postoperative hormonal status, and postoperative clinical status 2 weeks after surgery were analyzed. We performed a volumetric analysis of the tumor and the residual using a Brainlab workstation (iPlan [Brainlab AG, Heimstetten, Germany]).

Quantitative Variables. The clinical status was presented as Karnofsky Performance Status. The volume of the tumor/tumor residual was presented as volumetric analysis.

Descriptive Data

Participants. Between 2010 and 2017, 27 patients were operated on for resection of skull base chordomas in our institution, 15 of whom were operated on under iMRI control. Eleven patients were male, and 4 were female. The age ranged from 13 to 61 years (mean, 37 years).

Seven patients were previously operated on for tumor resection; 4 experienced progression of tumor remnant, 3 from resectable large residual tumors after previous surgeries. None of the patients had received radiation previously.

Thirteen patients reported headache; 3 had hemiparesis; 8 reported double vision, caused by abducent nerve palsy in 7 patients and combined abducent and partial oculomotor nerves palsy in 1 patient. The visual field was affected in 4 patients (Table 1).

Preoperative Radiologic Evaluation. Preoperatively, all patients underwent examination with magnetic resonance imaging (MRI) with and without contrast. Magnetic resonance angiography was performed to define the course of the internal carotid artery, which is crucial before transsphenoidal surgery. High-resolution computed topography with bone window was performed in all patients to evaluate the bony structures and extent of bone invasion. Because the tumors were located close to the sella, preoperative and postoperative hormonal evaluation was performed. None of the patients in this series had new hormonal deficiency. One patient had secondary hypothyroidism before surgery and was unchanged after surgery.

Patient Selection and Indication for Using iMRI. The indication for using iMRI for resection of skull base chordomas was mainly tumors with their main bulk in the clival region with minimal lateral extension to the temporal bone, middle fossa, and infratemporal fossa. Patients who had tumors that had mainly a lateral extension to the cerebellopontine angle were operated on in the semi-sitting position, which is not possible under iMRI control. Tumors that required a lateral position were not operated on under iMRI. In the preoperative preparation, patients who had implanted devices such as cardiac pacemakers or implanted MRI-incompatible metal parts were not operated on under iMRI control.

Tumor Extension. We evaluated the tumor extension based on preoperative radiologic evaluation and intraoperative findings. The tumor extension is described in Table 2. In 7 patients, there was a brainstem compression, and in 5 patients, there was an intradural extension. Nine patients had lateral tumor extension. The cavernous sinus was invaded in 4 patients. In 1 patient, the tumor extended to the middle cranial fossa.

Aim of Surgery. Safe maximal resection of the chordomas was the aim of surgery in all cases. In 8 patients (53%), gross total resection was surgically feasible and accordingly planned. In the other 7 patients (47%), complete tumor removal was not possible because of extension in the cavernous sinus (4 patients), petroclival fissure, and temporal bone (3 patients) (Table 2). In 2 patients, staged surgery was planned.

Table 1. Preoperative and Postoperative Criteria of the Patients

Patient Number	Preoperative Symptoms	Improvement of the Preoperative Symptoms	Postoperative New Deficits	Preoperative Karnofsky Status	Postoperative Karnofsky Status
1*	HD, CN III, VI, VF	HD, VF	—	80	80
2*	HD, CN VI, hemiparesis	Hemiparesis	—	60	80
3*	HD, ataxia, hemiparesis, CN VI	Coordination and hemiparesis	—	60	90
4	HD, CN VI, hemiparesis	HD, hemiparesis	—	60	90
5	HD	HD	—	90	100
6*	HD, VF	HD, VF	Partial sixth palsy, trigeminal hypoesthesia	100	100
7	HD	HD	—	90	100
8	HD	HD	—	90	100
9*	HD, lower cranial nerves	HD	—	80	80
10	HD, CN VI, VF	HD, CN VI, VF	—	80	100
11	Dizziness, CN VI	CN VI, dizziness	—	90	90
12	CN VI	CN VI	—	90	100
13	HD	HD	—	90	100
14*	HD	HD	—	90	100
15*	HD, VF, CN VI	HD, VF	—	80	90

HD, headache; CN, cranial nerve; VF, Field of vision.
*Previously operated patients.

Statistical Methods

The significance of the change in clinical status surgery was tested using a Fisher exact test. The correlation between the improvement of the clinical status (presented as Karnofsky Performance Status as a continuous variable) and the resected volume was tested using a Spearman correlation test. The association between the resection of the tumor component compressing or encroaching on the brainstem versus tumor invading the cavernous sinus and the improvement of clinical status was tested using a χ^2 test. The frequencies of the location of the residual tumor were described.

RESULTS

Surgical Preparation and Procedures

All the patients were operated on under 1.5-T iMRI control (Magnetom Espree Siemens AG Medical Solution, Munich, Germany, software NUMARIS/4 version syngo MR B17, AG Medical Solution, Munich, Germany). The head was fixed using an MRI-compatible head fixator. An initial iMRI (before tumor resection) was performed in all patients including high-resolution imagining (T1, T1 with contrast medium, T2, and fluid-attenuated inversion recovery imaging). The images were then transferred to a planning workstation (iPlan [Brainlab AG]). The presurgical MRI was fused with the preoperative computed tomography scan. The tumor was segmented, and volumetry was performed. The plan was sent to our navigation (Vector Vison Sky [Brainlab AG]) for further guidance during surgery.

In 12 patients, the endonasal endoscopically assisted approach was used. One patient was operated on via an anterior petrosal approach, 1 patient via the frontotemporal approach, and 1 patient via the retrosigmoid approach.

When the surgeon assumed that the goal of surgery had been reached, an iMRI control was performed. If satisfactory resection and decompression were still not achieved and the residual tumor was considered resectable, the remnant part was segmented, and the data were transferred to the navigation system. Further resection was carried out. Repeated iMRI controls were performed until the planned degree of resection was achieved. An immediate assessment of the degree of resection was always possible using iMRI.

Reconstruction of the skull base was required in 10 patients using an autologous fat graft. In 5 patients, prophylactic lumbar drainage was inserted for 5 days and was successfully removed. None of the patients in this series had cerebrospinal fluid leak, and no revision surgeries were required.

Extent of Tumor Resection

The aim was achieved and confirmed with iMRI in all surgeries. Gross total resection of the tumor was achieved in 8 cases, as planned. In the other 7 cases, total resection was not possible because of the extension of the tumor outside the corridor of the surgical approach; adequate debulking and decompression of the

Table 2. Tumor Extension, Target Components, Resected and Residual Volume, and Number of Intraoperative Magnetic Resonance Imaging Controls

Patient Number	Tumor Extension	Tumor Volume (cm^3)	Target Volume for Resection	Surgical Approach	Extent of Target Volume Resection	Extent of Tumor Resection	Residual Tumor Volume (cm^3)	Resected Volume (cm^3)	Percentage of Resection	Number of Intraoperative Magnetic Resonance Imaging Controls	Location of Residual Tumor
1	Whole clivus	11.4	GTR	Per nasal transsphenoidal	Complete	Complete	0	11.4	100	1	
2	Clivus, prepontine, intrapontine eft petroclival fissure	19.22	GTR	Per nasal transsphenoidal	Complete	Complete	0	19.22	100	3	First lower clivus, intradural, lateral Second intradural, lateral
3	Clivus, prepontine, intrapontine, petroclival fissure	11.015	Upper clivus, prepontine, intrapontine	Anterior transpetrosal	Complete	Subtotal	2.07	8.945	80.9	3	Intradural
4	Clivus, dorsum sellae, interpeduncular prepontine cyst, petroclival fissure	12.361	Clivus, prepontine	Per nasal transsphenoidal	Complete	Subtotal	1.04	11.321	91.8	1	
5	Clivus, prepontine	12	GTR	Per nasal transsphenoidal	Complete	Complete	0	12	100	2*	Posterolateral to the sella in the dorsum sellae
6	Dorsum sellae, petroclival fissure middle clivus	17.027	GTR	Pterional extradural	Complete	Complete	0	17.027	100	1	
7	Clivus, cavernous sinus bilaterally	20.43	Clivus, decompression of the cavernous sinus	Per nasal transsphenoidal	Complete	Partial	6.22	14.21	69.6	1	
8	Clivus, cavernous sinus bilaterally	23.42	Clivus, decompression of the cavernous sinus	Per nasal transsphenoidal	Complete	Partial	8.408	15.012	64	2	Resectable parts in the medial aspect of the cavernous sinus
9	Lower clivus, interdural, and intradural at the foramen magnum	10.011	GTR	Retrosigmoid	Complete	Complete	0	10.011	100	2	Intradural part of the tumor
10	Upper clivus, sphenoidal sinus, parasellar, petroclival fissure	24.2	GTR	Per nasal transsphenoidal	Complete	Complete	0	24.2	100	1	
11	Whole clivus, sphenoidal sinus, petroclival fissure bilaterally	21.4	GTR	Per nasal transsphenoidal	Complete	Complete	0	21.4	100	2	Lateral parts in the petroclival fissure
12	Upper clivus, prepontine, petroclival fissure	14.7	clivus	Per nasal transsphenoidal	Complete	Partial	4	10.7	72.7	1	
13	Upper and middle clivus, intradural prepontine	15	GTR	Per nasal transsphenoidal	Compete	Compete	0	15	100	1†	

14	Clivus, right cavernous sinus, right middle fossa, intradural	38	Clivus (a second section for transcranial resection was planned)	Per nasal transsphenoidal	Complete	Partial	22.1	15.9	39	1	
15	Clivus, cavernous sinus bilaterally	23.2	Clivus	Per nasal transsphenoidal	Complete	Partial‡	8	15.2	46.6	2	Dorsum sellae

GTR, gross total resection.
*This patient had a large clival vein that bled intensively during surgery. After tumor resection, which was confirmed by the first magnetic resonance imaging control, the hemostasis was secured, and intraoperative magnetic resonance imaging was performed again after insertion of the nasal tamponade to exclude bleeding and not to control the degree of resection.
†Only 1 intraoperative magnetic resonance imaging control was performed, which showed a small tumor residual in the lateral and cranial aspect of the resection cavity. The residual tumor could be inspected well and resected, and thus, second control was not necessary.
‡The degree of resection was planned according to the patient's wishes.

brainstem and/or the optic pathways were performed. The degree of tumor resection was also confirmed in the first postoperative MRI performed 2–3 months after surgery.

The target components were the clivus (15 patients), the petroclival fissure (8 patients), the intradural components and the parts compressing the brainstem (7 patients), and the medial part of the cavernous sinus (4 patients). The mean volume of the tumors was 18.1 cm^3 (standard deviation [SD], 7.4) and the mean volume of the residual tumor was 3.4 cm^3 (SD, 5.7). The mean volume of the resected tumor was 14.7 cm^3 (SD, 4.1 cm^3). The mean percentage of resection was 84.3% (SD, 20.4).

Number of iMRI Controls

In 8 patients (53.3%), the target components and volume were achieved and confirmed in the first MRI control. The first iMRI control showed a resectable residual tumor in 7 patients (46.6%). In 5 patients, the target was achieved and confirmed at the second MRI control. The target was reached in 2 patients after 3 MRI controls (Table 3). In 1 patient with large dural veins, in whom hemostasis was difficult, MRI was performed after completion of the procedure and insertion of the nasal tamponade to exclude active bleeding. The time required to perform iMRI control depends on the number of required MRI sequences. Preparation time before and after performing iMRI ranged from 10 to 15 minutes.

Locations of Residual Tumor that Required Further Resection

In 3 patients, the residual tumor was located in the clivus outside the surgical corridor: caudal to the resection corridor in 1 patient; and cranial in 2 patients. In 2 patients, the residual tumor was lateral to the corridor: in the petroclival fissure (1 patient) and in the medial aspect of the cavernous sinus (1 patient). In 4 patients, the control iMRI showed a residual intradural tumor. The resection of the intradural component required 1 iMRI control in 1 patient, 2 times in the second, and 3 times in the third and fourth (Figures 1 and 2). Thus, the intradural component required more frequent iMRI control (9 controls) compared with the lateral extension.

Surgical Outcome

Headache improved in 11 patients (84.6%). Two patients showed improvement of preoperative hemiparesis (66.6%), 1 patient experienced improvement of his coordination, and another reported improvement of dizziness (100%). The field of vision improved in 4 patients (100%). Abducent palsy improved in 3 patients. One patient showed new deficits after surgery, with abducent nerve palsy and trigeminal hypoesthesia without improvement within 2 weeks (6.6%) (Tables 1 and 4).

Results of the Statistical Analysis

The clinical status improved in all patients and the clinical status significantly improved after surgery (Fisher exact test; the result is significant at $P \leq 0.05$).

The improvement of clinical status showed a weak but not significant association with the resected tumor volume ($P = 0.4$). The improvement of the clinical status was significantly associated with the resection of the components that compressed the brainstem, including the intradural components ($P = 0.02$), but

Table 3. The Number of Magnetic Resonance Imaging Examinations in Relation to the Degree of Tumor Resection

Number of Controls to Confirm the Target Resection Volume	Number of Patients	Number of Gross Total Resection (%)	Number of Subtotal Resection (>80%) (%)	Number of Partial Resection (<80%) (%)
1	8	4 (50)	1 (12.5)	3 (37.5)
2	5	3 (60)	0	2 (40)
3	2	1 (50)	1 (50)	0

was not associated with the resection of the lateral extension of the tumor ($P = 0.75$).

DISCUSSION

Chordomas are characterized by slow yet progressive local growth. Untreated patients die of progressive local growth estimated within 12 months after the diagnosis.[32] Recurrence is typically local but recurrence along the operation tract and systemic metastasis have been described.[46-49]

Total tumor resection of skull base chordomas, when possible, is associated with better overall survival and progression-free survival.[50] It is associated with a higher rate of morbidities, which can adversely affect the long-term functional outcome and quality of life.[14,19] The risk of postoperative morbidity is linked to large or giant tumor diameter, irregular growth pattern, and previous treatment, including surgery or radiation.[16,33] Although modern skull base approaches have reduced the mortality and morbidity associated with the resection of chordomas,[23] chordomas are regarded as not surgically curable tumors,[19] especially in cases of widely invasive tumor.[14,15,17,33] In cases of irresectable tumors, the aims of surgery are a pathologic diagnosis, debulking, decompression of vital structures, including the brainstem, and creation of space between radiosensitive structures such as the brainstem or the optic nerve and the tumor to decrease the radiation side effects.[15,20,33] Residual tumor is managed using

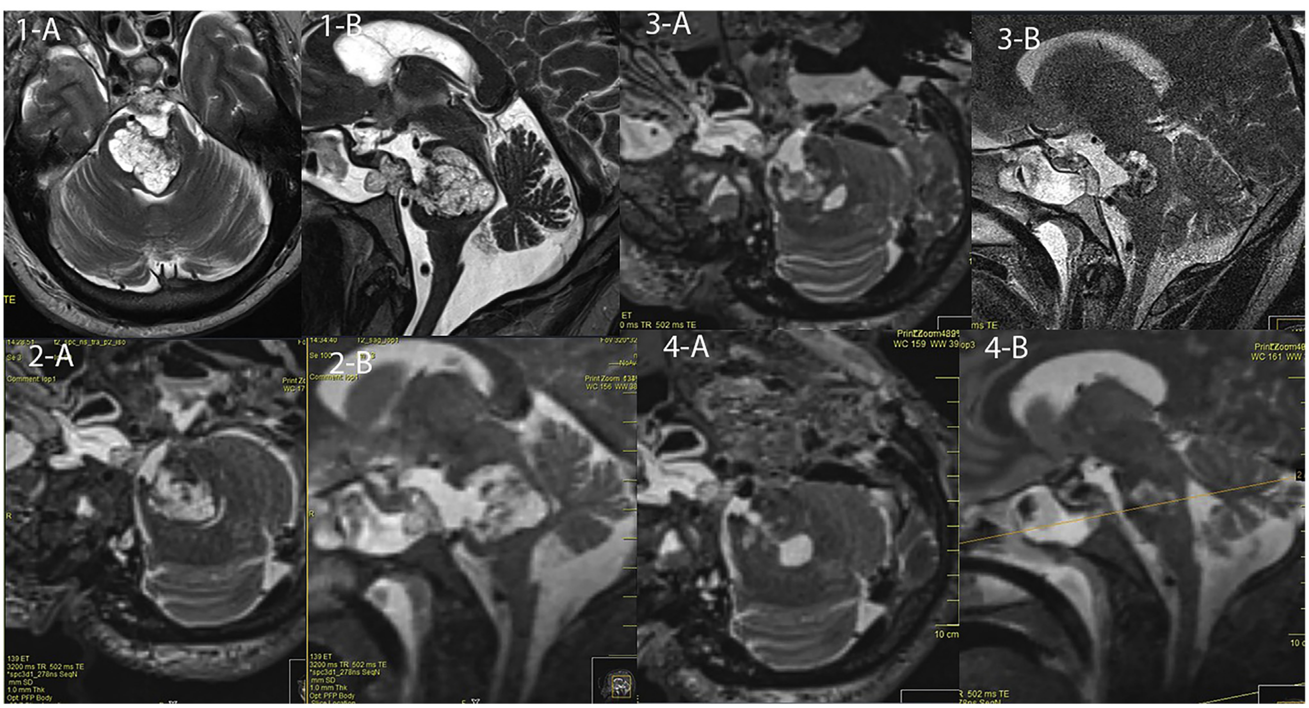

Figure 1. A previously operated patient with residual tumor encroaching on the brainstem (**1-A, 1-B**). The patient was operated on via a left anterior petrosal approach and the first intraoperative magnetic resonance imaging after initial tumor resection showed residual tumor (**2-A, 2-B**), which was progressively resected (3-A, 3-B) until complete removal (**4-A, 4-B**). The patient had residual tumor in the upper clivus, which was resected in another session via a transsphenoidal approach.

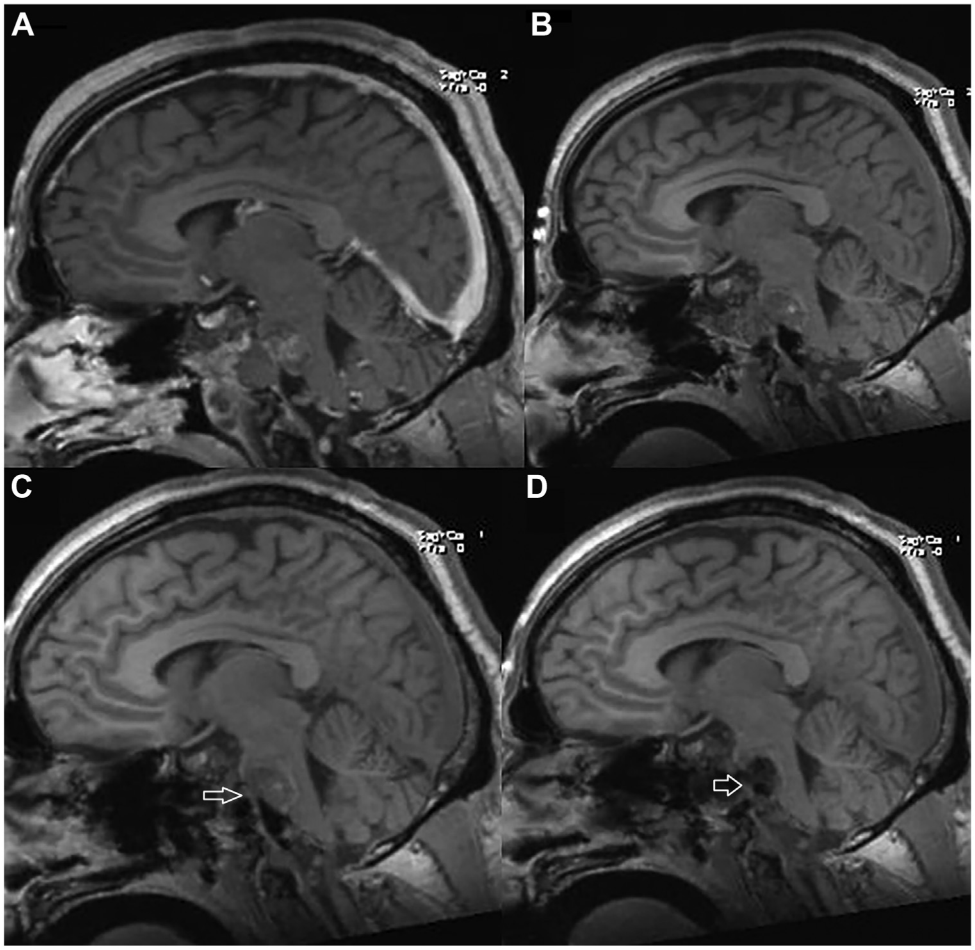

Figure 2. A patient with clival chordoma with intradural extension and encroachment on the brainstem (**A**). The first intraoperative magnetic resonance imaging after initial tumor resection showed residual tumor (**B**), which was progressively resected and the third control showed still intradural component (*arrow* in **C**), which was completely removed (*arrow* in **D**).

radiation, and the response to radiation depends on the volume of the tumor.[15,17] Nevertheless, there is no therapeutic consensus for the management of skull base chordomas.[17,22,34] In this retrospective study, we evaluated a series of 15 patients operated on for resection of skull base chordomas using iMRI control. The degree of resection of the target volume, the residual tumor volume, and the outcome and the course of the neurologic deficits were analyzed.

Table 4. The Preoperative Symptoms and the Percentage of Postoperative Improvement

Preoperative Symptom (Number of Patients)	Percentage of Improvement
Headache (13)	84.6
Hemiparesis (3)	66.6
Visual field defects (4)	100
Coordination disturbances or dizziness (2)	100
Sixth palsy (8)	37.5

iMRI can give near real-time feedback about the completeness of the resection or the volume and location of the residual tumor. This information can be integrated into the neuronavigation to guide further resection. In 7 patients, the surgery was continued after the first iMRI control was performed, which showed a resectable residual tumor. The most frequent location of the residual tumor was the intradural part (3 patients). Resection of the intradural part also required repeat iMRI to confirm the completeness of the resection; 3 controls in 1 patient, 2 controls in the second, and 1 control in the third. In 2 patients, resection of the tumor continued after the first control because of the presence of resectable residual tumor in the petroclival fissure (1 patient) or the medial part of the cavernous sinus (1 patient). In 2 patients, iMRI showed a residual tumor in the dorsum sellae that required further resection. In 1 patient, the residual tumor was in the clivus caudal to the surgical corridor. All effort should be made to ensure resection of the tumor as much as possible. Beside iMRI, operative endoscopy can be a good visualization tool. Nonetheless, it has some limitations because of the difficulty in quantifying the volume of the tumor residual and the degree of resection if partial resection is planned. In 5 patients, endoscopic-assisted surgery was performed. However, iMRI added more information about the presence, size, and location of the residual. We believe that the operative endoscope complements iMRI, thus helping to maximize the degree of resection in a dedicated operation room.[36] After iMRI control, the residual can be localized by navigation and resection under microsurgical or endoscopic control. However, iMRI is not a replacement for the operative endoscope or neuronavigation. iMRI plays a complementary role in multimodal intraoperative visualization.

IMRI helped achieve gross total resection in 4 patients (50%) who required repeat iMRI control. In 1 patient, subtotal resection (>80%) required 3 iMRI controls. Optimized partial resection was achieved in 2 patients.

Decompression of the brainstem and resection of the intradural part had a significant association with the improvement of clinical status. In 3 patients (60%), the intradural component was successfully resected with the help of repeat iMRI control. Because of the associated high rates of complications during resection of the intracavernous part of the tumor, we did not plan or pursue complete resection.

iMRI has a high value even in experienced hands to prevent unnecessary tumor residual. The rate of gross total resection ranged in most of the reported series between 71.6% and 0%.[17,19,23,27,29-31,33-36,42] In this series, complete resection of the tumor was achieved in 8 patients (53.3%). Complete resection of the target volume was possible in all cases. The mean percentage of the degree of tumor volume reduction was 83%. The possibility of total tumor resection, even under iMRI, is related to the invasiveness of the tumor, which can extend outside the corridor of the surgical approach, including lateral tumor extension in tumors operated on via a transsphenoidal approach.

The functional outcome was satisfactory in all patients. The clinical status improved significantly after surgery. Three patients experienced improvement of hemiparesis after tumor resection and 2 patients reported an improvement in balance. Furthermore, 3 patients with preoperative visual field defects improved after surgery. One patient experienced new temporary abducent nerve palsy, which recovered after 3 months. None of the patients had permanent new neurologic deficits. The functional outcome is better in this series than that reported in other studies.[19,26,28] The resection of the tumor parts compressing the brainstem including intradural components was significantly associated with improvement of clinical status. Nevertheless, improvement of clinical status is not associated with tumor volume or resected volume. Accordingly, targeted debulking of the tumor, when complete resection is not feasible, is important.

Another possible intraoperative imaging technique is intraoperative computed tomography (iCT), which can provide good details about the osseous structures. The usability of iCT for resection of skull base chordoma could be questionable because of its low quality for imaging of soft tissue. Radiation exposure is also an issue when using iCT.

Technical Limitations and Bias

Positioning of the patient and selection of approach are limited because of the nature of the operating table and the head fixation system. Special positioning, such as park bench and semi-sitting, is not feasible. Approaches to the clival chordoma, including the retrosigmoid or far lateral approach, are therefore difficult. However, endonasal and anterolateral approaches are feasible. These approaches should be considered when selecting patients to be operated on under iMRI control.

Interpretation of iMRI is sometimes challenging because of heterogeneity of the lesion and its signals in MRI, inhomogeneous contrast enhancement, and presence of blood in the resection cavity. Evaluation of different MRI sequences is required to detect tumor remnant. The surgical field should be cleaned of blood before iMRI control is performed. We place, when possible, Spongostan (Johnson & Johnson Medical GmbH, Ethicon Deutschland, Norderstedt, Germany) in the resection cavity to prevent blood collection during MRI measurement. Furthermore, we use a bone wax plate in the resection cavity for orientation. The results of iMRI were validated using inspection of the resection cavity and also in the postoperative MRI performed 2–3 months after surgery (i.e., in this series there were no false-positive or false-negative results).

Functional outcome is a priority, and the surgeon tries to ensure the patient's safety. For this reason, the surgeon might tend to perform an iMRI control and not pursue an extensive resection, as they might do if iMRI is not available. It could be a bias when reporting the number of iMRI controls.

Cost-effectiveness is an important point of discussion. The availability of iMRI is limited to specialized centers worldwide. However, the number of available scanners increased recently. The cost-effectiveness aspects of iMRI have been discussed in previous studies.[51-53] Nevertheless, multicenter studies including different cranial diseases are required.

CONCLUSIONS

This study shows that iMRI is a safe method for intraoperative assessment of the degree of resection and the volume and location of the residual tumor in skull base chordomas. Thus, iMRI may help the surgeon to avoid leaving unnecessary tumor residual and to confirm the completeness of tumor resection. When gross total resection of the tumor is not feasible, iMRI can be a useful tool for targeted tumor resection and for confirming the degree of resection and adequacy of decompression of neural structures, especially the brainstem, which is particularly associated with improvement of clinical status.

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