Intraoperative MRI guidance and extent of resection in glioma surgery: a randomised, controlled trial

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Summary

Background **Intraoperative MRI is increasingly used in neurosurgery, although there is little evidence for its use. We aimed to assess efficacy of intraoperative MRI guidance on extent of resection in patients with glioma.**

Methods **In our prospective, randomised, parallel-group trial, we enrolled adults (≥18 years) with contrast enhancing gliomas amenable to radiologically complete resection who presented to Goethe University (Frankfurt, Germany). We randomly assigned patients (1:1) with computer-generated blocks of four and a sealed-envelope design to undergo intraoperative MRI-guided surgery or conventional microsurgery (control group). Surgeons and patients were unmasked to treatment group allocation, but an independent neuroradiologist was masked during analysis of all preoperative and postoperative imaging data. The primary endpoint was rate of complete resections as established by early postoperative high-field MRI (1·5 T or 3·0 T). Analysis was done per protocol. This study is registered with ClinicalTrials.gov, number NCT01394692.**

Findings **We enrolled 58 patients between Oct 1, 2007, and July 1, 2010. 24 (83%) of 29 patients randomly allocated to the intraoperative MRI group and 25 (86%) of 29 controls were eligible for analysis (four patients in each group had metastasis and one patient in the intraoperative MRI group withdrew consent after randomisation). More patients in the intraoperative MRI group had complete tumour resection (23 [96%] of 24 patients) than did in the control group (17 [68%] of 25, p=0·023). Postoperative rates of new neurological deficits did not differ between patients in the intraoperative MRI group (three [13%] of 24) and controls (two [8%] of 25, p=1·0). No patient for whom use of intraoperative MRI led to continued resection of residual tumour had neurological deterioration. One patient in the control group died before 6 months.**

Interpretation **Our study provides evidence for the use of intraoperative MRI guidance in glioma surgery: such imaging helps surgeons provide the optimum extent of resection.**

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Introduction

Interest in the use of intraoperative MRI in neurosurgery has increased in the past decade.[1] Several reports claimed such guidance was useful for intraoperative detection of unintentionally remaining tumour tissue, leading to a need for further tumour resections.[2–5] Moreover, some groups have reported survival benefits when extent of resection was used as a prognostic factor.[6–8] Additionally, investigators of a multicentre phase 3 trial comparing fluorescence guided microsurgery with conventional microsurgery of glioblastomas showed a survival benefit in patients who underwent complete tumour resection according to the assessment of residual contrast enhancement on postoperative MRI.[9,10]

However, the level of scientific evidence for use of intraoperative MRI guidance is low. Only one retrospective comparison between guided and conventional microsurgical procedures, undertaken in a consecutive series of patients, showed a benefit in terms of extent of resection.[11] The number of patients in this study was low and allocation to treatment groups might have been biased. Thus, we aimed to assess whether use of intraoperative MRI guidance leads to a higher rate of radiologically complete tumour resections than does conventional microsurgical tumour resection.

Methods

Study design and patients

We undertook a prospective randomised, parallel-group, controlled trial, the design of which has been reported elsewhere.[12] Adults (≥18 years) with known or suspected gliomas showing distinct contrast enhancement on T1-weighted MRI amenable to radiologically complete resection were eligible. Before inclusion, patients were assessed by neurosurgeons and anaesthesiologists for their suitability to undergo general anaesthesia for brain tumour surgery. If patients were not eligible (eg, presence of cardiopulmonary or hepatorenal comorbidities) patients were offered stereotactic biopsy instead of tumour resection. Other exclusion criteria were tumours that crossed the midline or were located in the basal ganglia, cerebellum, brain stem, or otherwise in close proximity to eloquent brain structures prohibiting or questioning complete resectability; contraindications to MRI examination (eg, pacemaker); and inability to give consent because of neuropsychological deficits or a language barrier. All patients provided written informed consent. The study was undertaken at the Goethe University (Frankfurt, Germany) with approval from the local ethics committee (approval number 239/07) in adherence to the Declaration of Helsinki.

For the **study protocol** see http://www.kompetenznetz-leukaemie.de/uct_trial/pdf/uct_de/kurzprotokoll_.pdf?id=44

Randomisation and masking

We randomly allocated patients in a one-to-one ratio to undergo either tumour resection with intraoperative MRI guidance or with conventional microneurosurgical techniques. Randomisation was done in patients in blocks of four using BiAS for Windows 9.01 by an assistant who had no clinical involvement in the trial. Investigators who assessed eligibility of patients and scheduled surgeries as a panel (KF, HV, TG, VS) were masked to treatment group assignment by use of a sealed-envelope design. CS, KF, and TG enrolled patients after surgery was scheduled and after written consent was obtained, usually on the day before the operation. Surgeons and patients were not masked to the treatment group assignment, but the neuroradiologist (AB) who analysed MRI data was masked. CS, KF, HV, TG, and VS assessed clinical outcomes of patients. AB did not have access to clinical data for the patients.

Procedures

12 neurosurgeons did the surgeries. For statistical comparisons, surgeons were classified as junior before, and senior after obtaining board certification. Junior surgeons were always supervised by senior neurosurgeons when performing tumour resections. Of 12 neurosurgeons, three were in training before obtaining board certification; two surgeons obtained their board certification while the study was ongoing and performed surgeries before and after their respective board examinations; and seven were board certified when the trial had started. We used a mobile intraoperative ultra-low-field MRI system (PoleStar N-20, Odin Medical Technologies, Yokneam, Israel and Medtronic, Louisville, CO, USA)[13,14] for procedures guided by intraoperative MRI. Conventional microneurosurgical resection included the use of all standard neurosurgical instruments and techniques (eg, use of an ultrasonic aspirator and neuronavigation system). Two different neuronavigation systems were available (StealthStation [Medtronic] and VectorVision [BrainLAB, Heimstetten, Germany]). Surgeons chose which system to use. The use of intraoperative ultrasound or fluorescence-guided surgery with 5-aminolaevulinic acid[9] was not allowed in either group. Postsurgical treatment was done according to standard protocols and clinical guidelines, dependent on tumour histology, previous treatment, and preferences of the patient. All patients were followed-up with clinical and MRI examinations every 3 months.

The primary endpoint was extent of resection. All patients underwent high-field MRI at 1·5 T or 3·0 T with and without contrast agent within 7 days before surgery and within 72 h after surgery. One masked, independent, and experienced neuroradiologist (AB) assessed MRIs to establish the extent of resection and undertake volumetric analyses of the tumours and tumour residues. Residual tumour was defined as detectable contrast enhancement on T1-weighted imaging with a volume of more than 0·175 cm³ on postoperative MRI as done previously.[9]

Secondary endpoints were the volume of residual tumour on postoperative MRI and progression-free survival (PFS) at 6 months. We also compared the duration of surgery and treatment-related morbidity.

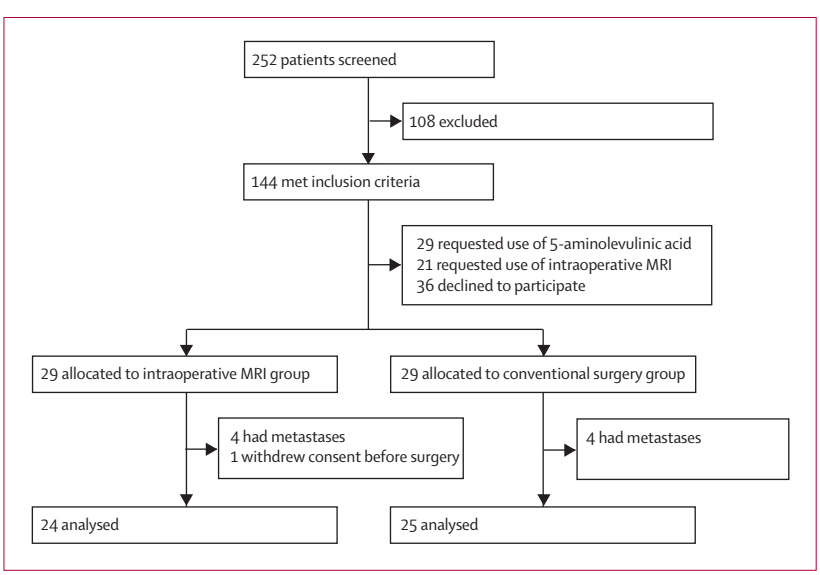


Figure 1: **Trial profile**

Statistical analysis

We compared binomial dichotomised data with Fisher's exact test. We compared differences between groups in age, Karnofsky performance status score, and tumour volumes with Student's *t* test or the Wilcoxon-Mann-Whitney *U* test. We did univariate analyses of factors potentially affecting PFS with the Kaplan-Meier method and a Cox regression model for multivariate analyses. The sample size calculation was done to detect a difference of 25% between groups for the primary endpoint with a power of 80%. After inclusion of half of the intended sample size (originally 80 patients), an interim analysis of the primary endpoint data was done, resulting in an adjustment of the sample size to 58. Due to the possible effect of this adjustment on the alpha error and to avoid overinterpretation of the data, we regarded p values of less than 0·04 as significant for the primary endpoint. For all other analyses, p values of less than 0·05 was regarded as significant, because they were not affected by the interim analysis. Statistical analyses were done with BiAS for Windows 9.01 and SPSS version 19.0.

This study is registered with ClinicalTrials.gov, number NCT01394692.

Role of the funding source

There was no funding source for this study. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results

We enrolled 58 patients between Oct 1, 2007, and July 1, 2010; one patient who was randomised to undergo intraoperative MRI-guided surgery withdrew consent before surgery. Eight patients had metastases on histopathological assessment (four patients in each group). Thus, data for 49 patients with glioma could be analysed (figure 1, table 1). In the intraoperative MRI group, 22 patients had glioblastoma (all WHO grade IV), one had ganglioglioma (grade I), and one an anaplastic astrocytoma (grade III). In the conventional treatment group, 22 patients had glioblastoma (all grade IV), two had gliosarcoma (grade IV), one had an anaplastic oligodendroglioma (grade III). Median preoperative tumour volumes did not differ between groups (17·7 cm³ [range 0·3–74·9, IQR 5·6–49·1] for the intraoperative MRI group *vs* 21·1 cm³ [1·0–67·0, 6·4–37·7] for the control group, p=0·88; figure 2). No patients were lost to follow-up.

In the intervention group, intraoperative imaging led to extended tumour resection in eight (33%) of 24 patients. Complete tumour resections were achieved in 23 (96%) of 24 patients in the intraoperative MRI group compared with 17 (68%) of 25 patients in the control group (p=0·023 [Fisher's exact test], odds ratio 0·092 [95% CI 0·014–0·602]).

38 (78%) of 49 procedures were done by senior neurosurgeons. Junior neurosurgeons did eight intraoperative MRI-guided procedures and three conventional tumour resections (p=0·17 [Fisher's exact test]). Rate of complete resections did not differ between senior neurosurgeons (32 [84%] of 38) and junior neurosurgeons (eight [73%] of 11, p=0·40 [Fisher's exact test]; webappendix).

Of the two available neuronavigation systems, one (StealthStation) is connected to the intraoperative MRI device and therefore was used in every case in the intervention group. In the conventional group, both neuronavigation systems were available, but were used in only 12 (48%) of 25 procedures. In a post-hoc exploratory analysis, we noted that early postoperative MRI showed residual tumour tissue in four (33%) of these 12 patients. Residual tumour could also be detected in four (31%) of 13 patients in the conventional group in whom neuronavigation was not used. This difference was not significant (p=1·0 [Fisher's exact test]). Nevertheless, the benefit of intraoperative MRI-guidance remained in terms of extent of resection between the intraoperative MRI group and individuals in the control group in whom neuronavigation was used (p=0·042 [Fisher's exact test]).

The median postoperative volume of contrast enhancing tissue was 0 cm³ (range 0–0·19 cm³) in the intraoperative MRI group and 0·03 cm³ (0–1·76 cm³) in the conventional group (p=0·0015; figure 2). The residual tumour in the one patient in the intraoperative MRI group who did not achieve complete resection corresponded to 1·2% of the original tumour volume. For the eight patients in the conventional group for whom complete resection was not achieved, residual tumour corresponded to 0·7–13·5% of the original tumour volumes.

At 6 months, 16 (67%) of 24 patients in the intraoperative MRI group were stable and eight (33%) had progressed, compared with nine (36%) of 25 patients who were stable in the conventional group and 16 (64%) who had progressed (including one death). Fewer patients had progressive disease in the intraoperative MRI group than the conventional group (p=0·046 [Fisher's exact test], odds ratio 0·281 [95% CI 0·087–0·906]).

Kaplan-Meier estimates of PFS suggested a median of 226 days (95% CI 0–454) in the intraoperative MRI group and 154 days (60–248) in the conventional group, but this did not differ significantly (p=0·083; figure 3). Patients who underwent a complete tumour resection had a longer PFS than did patients with residual tumour (median 226 days [162–290] *vs* 98 days [92–104], p=0·003; figure 3).

We did a post-hoc exploratory analysis of the 37 patients with primary WHO grade IV tumours to account for differences in histology and adjuvant treatment after surgery in the whole cohort. Kaplan-Meier estimates

See Online for webappendix

	Intraoperative MRI group (n=24)	Conventional treatment group (n=25)
WHO grade		
I	1	0
II	0	0
III	1	1
IV	22	24
Sex (male)	16 (67%)	14 (56%)
First surgery	20 (83%)	19 (76%)
Mean age (range, SD)	55·3 (38–76, 12·5)	55·0 (30–84, 13·6)
Median KPS score (range, IQR)	90 (60–100, 80–100)	90 (70–100, 85–95)

Data are n or n (%), unless otherwise stated. KPS=Karnofsky performance status.

Table 1: **Patients' demographics**

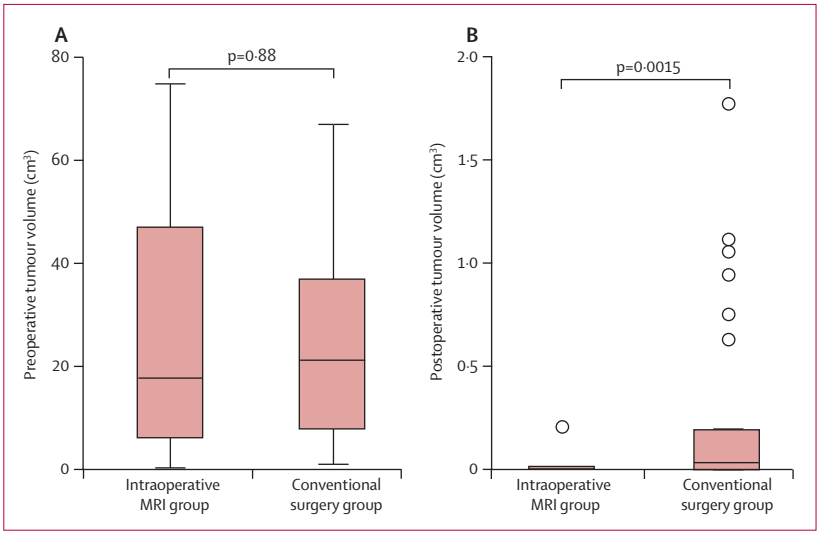


Figure 2: **Preoperative and postoperative tumour volumes**
Preoperative (A) and postoperative (B). p values were calculated with the Wilcoxon-Mann-Whitney *U* test.

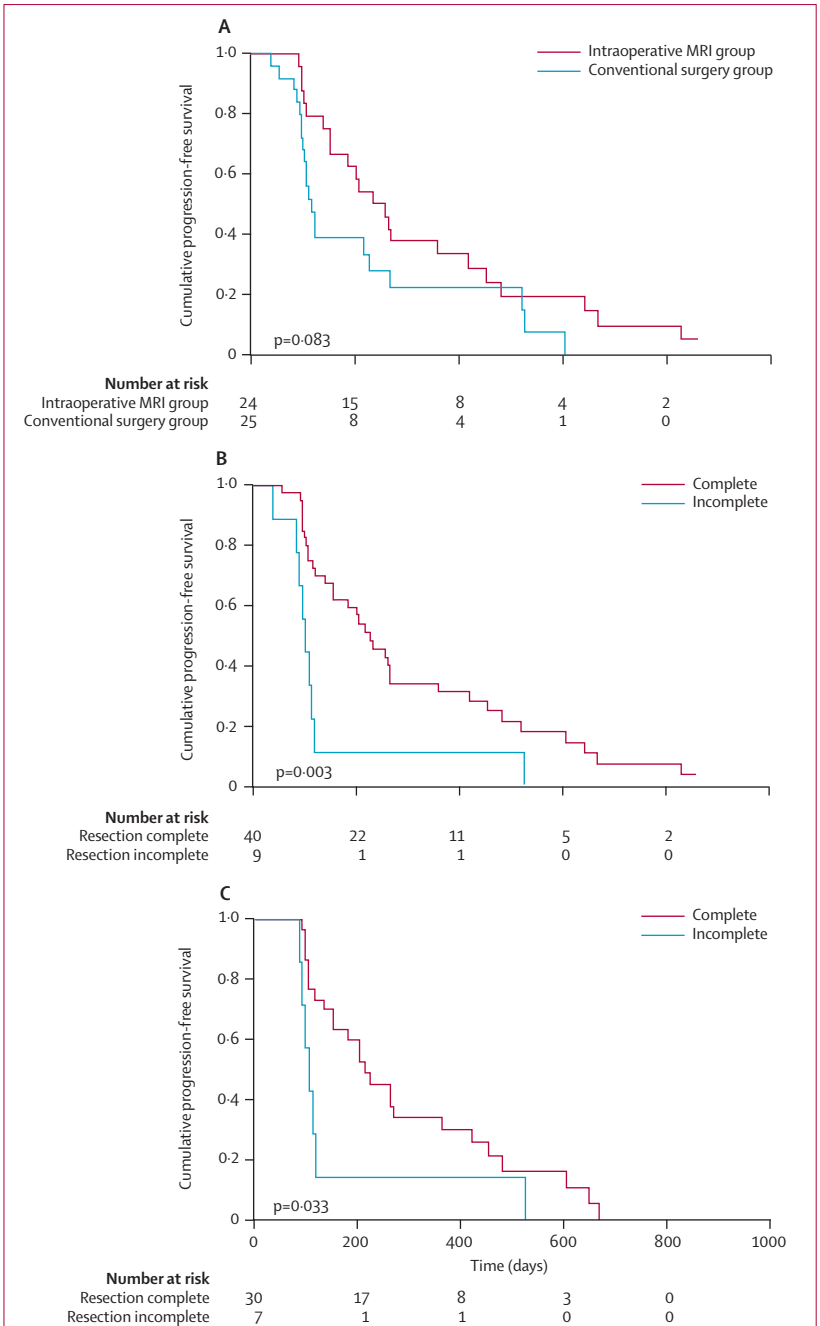


Figure 3: **Kaplan-Meier curves of progression-free survival**
Progression-free survival by treatment group (A), by extent of resection (B), and by extent of resection in a subgroup of 37 patients with primary WHO grade IV tumours (C). p values were calculated with the log-rank test.

showed a median PFS of 218 days (95% CI 143–293) for the 30 such patients undergoing complete resection compared with 110 days (79–141) for the seven such patients with residual tumour (p=0·033; figure 3). However, this difference did not persist after stratification between treatment groups (median 202 days for intraoperative MRI group and 115 days for the conventional group, p=0·38 [log-rank test]).

	Progression-free survival (days)*	Univariate p value†	Multivariate p value‡
Age		0·37	0·77
<55 years	226 (0–454)	..	..
≥55 years	154 (60–247)	..	..
Sex		0·874	0·55
Male	119 (25–213)	..	..
Female	226 (155–297)	..	..
KPS score		0·31	0·53
70	98 (0–405)	..	..
80	139 (90–188)	..	..
90	115 (23–207)	..	..
100	361 (45–677)	..	..
WHO grade		0·24	0·33
I and III, pooled	259 (0–611)	..	..
IV	185 (103–267)	..	..
Tumour type		0·72	0·45
Primary tumour	202 (125–279)	..	..
Recurrent tumour	119 (0–300)	..	..
Extent of resection		0·003	0·005
Complete	226 (162–290)	..	..
Incomplete	98 (92–104)	..	..
Surgeon experience		0·46	0·40
Junior	154 (0–325)	..	..
Senior	202 (114–290)	..	..

Data are mean (95% CI), unless otherwise stated. KPS=Karnofsky performance status. *Kaplan-Meier analysis. †Log-rank test; ‡Cox regression analysis.

Table 2: **Association of demographic factors with progression-free survival**

Other potential prognostic factors (age, sex, WHO grade, recurrent tumour, Karnofsky performance status score, experience of surgeon) did not affect PFS (p>0·1; table 2). On multivariate analysis, extent of resection was the only factor that affected PFS (p=0·005).

Time of surgical procedure, measured from skin incision to wound closure, was slightly longer in the intraoperative MRI group (mean 250 min [SD 62·1]) than it was in the control group (227 min [75·8]), but this difference was not significant (p=0·26 [Student's *t* test]). However, the overall time spent in the operating room, including anaesthesia induction and preparation, was longer in the intraoperative MRI group (mean 429 min [SD 77·8]) than it was in the conventional group (362 min [86·5], p=0·007 [Student's *t* test]).

Postoperative new or aggravated neurological deficits occurred in five (10%) of 49 patients (table 3). Two (8%) of 25 patients in the conventional group and three (13%) of 24 patients in the intraoperative MRI group had complications (p=1·0 [Fisher's exact test]); however, intraoperative imaging had not led to continuation of tumour resection in any of these patients. Two patients became symptomatic with rebleedings, which are not attributable to the use of intraoperative MRI. In one patient, haemianopia was deliberately accepted due to tumour extension around the temporal horn of the lateral

	Treatment group	Age (years)	Histology	Tumour location	Preoperative tumour volume (cm³)	Postoperative tumour volume (cm³)	Percent residual tumour	Continued resection after intraoperative MRI scanning	Details of deficit	Status at 6 months
Patient 11	Conventional group	58	Glioblastoma	Left temporal	19·19	0·92	4·8%	..	Mild aggravation of pre-existing aphasia	Alive, stable disease
Patient 21	Intraoperative MRI group	50	Glioblastoma	Right frontal	17·92	0	0%	No	Psychotic episode	Alive, progressive disease
Patient 26	Conventional group	84	Anaplastic oligodendroglioma	Right temporal	27·36	0·20	0·7%	..	Rebleeding, aphasia, and seizures	Dead
Patient 31	Intraoperative MRI group	74	Glioblastoma	Left temporal	35·19	0	0%	No	Rebleeding and aphasia	Alive, stable disease
Patient 45	Intraoperative MRI group	45	Recurrent glioblastoma	Left temporal	57·68	0	0%	No	Haemianopia	Alive, progressive disease

All patients were male and were operated on by a fully trained surgeon.

Table 3: **Details of patients with complications**

ventricle involving the optic radiation. We did not note wound infection in any patient.

Discussion

Intraoperative MRI is used to depict residual tumour tissue during an operation, enabling surgeons to selectively continue tumour resection. In our prospective, randomised, controlled trial we noted a beneficial effect of guidance with intraoperative MRI for complete resection of contrast enhancing primary brain tumours compared with conventional microsurgery, with an associated increase in PFS.

Gross total resection as measured by absence of contrast enhancing tumour after surgery is associated with extended overall survival and PFS in low-grade and high-grade gliomas.[15–17] The need to improve intraoperative visualisation of tumour tissue was confirmed after Albert and colleagues[18] reported strikingly high rates of incorrect assumptions made by surgeons about the extent of resections. Intraoperative MRI systems were therefore developed as surgical techniques to help visualise tumour remnants that would otherwise remain unresected.[19]

The first intraoperative MRI unit was installed at the Brigham and Women's Hospital in Boston (MA, USA) and many other installations have followed.[20,21] Dependent on the type of intraoperative MRI system, installation costs US$3–8 million. Additionally, surgery with intraoperative MRI guidance has been reported to be more time-consuming than is conventional surgery,[5] adding costs to every procedure. In our trial, intraoperative MRI guided surgery added about 1 h to conventional surgery. Intraoperative image acquisition can usually be done within a few minutes with the PoleStar low-field intraoperative MRI unit because of placement of the magnet underneath the patient's head during surgery, but preparation of the operating room and positioning of the patient in the MRI-compatible head holder are more difficult than is placing the patient's head in a regular head fixation (eg, a Mayfield or Doro clamp).[5] Time demands might be different when other intraoperative MRI devices are used; for example, if the patient needs to be transferred to an adjacent room for scanning.

The true value of intraoperative MRI guidance in modern neurosurgery has not been scientifically validated (panel).[22] Until now, only retrospective cohort series have shown a positive effect of such guidance on extent of resection in brain tumour surgery by showing remaining tumour tissue.[2,3,5,11,23,24] Nonetheless, imaging sequences are not always done when a surgeon believes that they have resected the initially intended amount of tumour, and resection is reportedly continued in 10–70% of cases in which an intraoperative MRI (irrespective of design or field strength) is used, implying that there is frequently a bias to scan early simply because imaging is available.[21] Thus, scientific evidence is needed to justify the use of such expensive technology.[21,25] Accordingly, our primary outcome was not the number of cases in which intraoperative MRI led to continuation of resection, which could have been biased, but rather was extent of resection on postoperative MRI, which is an objectively equivalent variable when the aim of surgery is complete resection. To compare our findings with the previously published work, we chose primary and secondary endpoints that have been used before in a multicentre trial that compared conventional resection with fluorescence guided resection of primary brain tumours.[9]

Intraoperative imaging led to continued resection of contrast enhancing tissue in a third of patients in the intraoperative MRI group. Had intraoperative imaging not been used, the resection rates between treatment groups would no longer differ significantly. The beneficial effect of intraoperative MRI is probably due to the ability to reassess neuronavigation during surgery. Neuronavigation is usually based upon preoperative imaging, and anatomy is altered during surgery due to resection of tissue and loss of cerebrospinal fluid. These alterations, so-called brain-shift, render conventional neuronavigation somewhat inaccurate after dura opening and during tumour resection. Therefore, tumour remnants can be overlooked. Intraoperative imaging can be used to depict

Panel: **Research in context**

Systematic review

Before starting this trial, we searched the PubMed database without language or date restrictions with the search terms "intraoperative MRI", "glioma surgery", and "extent of resection", with associated alternatives (eg, brain tumour in place of glioma) to identify reports on this topic. We assessed all relevant articles and gauged the level of scientific evidence provided. We found no randomised controlled trials of the use of intraoperative MRI in brain tumour surgery, irrespective of the field strength or design of the MRI device. Several retrospective reports and case series (evidence level III–IV) documented the benefit of implementation of intraoperative MRI in the neurosurgical routine in glioma surgery by means of increasing the extent of resection, but high-level evidence in terms of prospective randomised studies that might prove the benefit of intraoperative MRI compared with standard microneurosurgical resection of brain tumours was absent.

Interpretation

Our study provides evidence to justify the use of intraoperative MRI guidance in glioma surgery: such imaging helps surgeons provide the optimum extent of resection. In this study, we also report a benefit in progression-free survival for patients undergoing complete resection, supporting the belief that extent of resection is important for patients with gliomas. Clinicians should consider use of either intraoperative MRI guidance or 5-aminolaevulinic acid fluorescence (or a combination) in the resection of malignant brain tumours to achieve the best surgical result possible, taking into account that an extensive tumour resection will only prolong life and not provide cure from the disease.

these remnants, and restore the accuracy of neuronavigation. In our study, extent of resection in the intraoperative MRI group was better than it was in the control group even after exclusion of surgeries done without the use of a neuronavigation system.

Importantly, our data show that this enhanced resection was not achieved at the cost of increased surgical morbidity. The overall complication rate in this study was within previously reported limits,[26] and complications did not occur in patients in whom intraoperative MRI led to continued resection of tumour tissue. Use of intraoperative MRI thus improves the neurosurgeon's goal of extensive but safe tumour resection. Notably, the extent of resection in the conventional group of this study was higher (complete resection in 68%) than it was in the conventional group of the study by Stummer and colleagues (complete resection in 36%), applying identical criteria to define residual tumour,[9] suggesting that there was no negative treatment bias in our control group.

Our study was designed to show the effect of intraoperative MRI in ideal conditions (ie, no tumour misdiagnoses). However, conventional imaging techniques are not capable of distinguishing reliably between contrast-enhancing gliomas and cerebral metastases, and therefore patients with cerebral metastases were erroneously randomised. We chose to exclude these patients from the final analysis because the intraoperative features of metastases usually differ substantially from glial tumours, and high rates of complete resection can be achieved without the need for continuing tumour resection after intraoperative image acquisition.[27] However, the benefit of intraoperative MRI that we noted would have remained significant if we had kept metastases in the final analysis of the primary endpoint. Similarly, we did not believe it would have been appropriate to include patients with cerebral metastases in the analysis of PFS. Although complete resection of a single cerebral metastasis is reportedly associated with better local control,[28] the outcome of patients with metastases depends mainly on the underlying primary tumour and the extracerebral status of the disease, which cannot be influenced by neurosurgical intervention, and the overall survival is usually worse than is that of patients with glioma.[27,29]

Even if extent of resection is only a surrogate parameter of clinical benefit for patients with brain tumour, it is associated with extended overall survival (at least in high-grade gliomas).[30,31] In our study, complete tumour resection corresponded to an extended PFS on univariate and multivariate analysis and was, again,[9] a stronger prognostic factor than age. The effect of intraoperative MRI on decrease in the median residual tumour volumes might seem small, but reports suggests that cells at the tumour periphery exert a greater effect on outcomes of patients with glioma than do those cells in the tumour centre.[32,33] However, our study was not powered or designed to show effects of extent of resection on overall survival of patients with gliomas. A large-sale study needs to explicitly address the question of whether intraoperative MRI influences survival.

One inherent limitation of this study is that it was not done in a double-blind manner, which is practically unfeasible in a trial comparing surgical techniques; however, outcome assessment (volumetric analyses and measurements of extent of resection) was done by an independent reader who was masked to treatment allocation. Our findings might also be restricted by the fact that our study was done at only one centre. However, various surgeons did the operative procedures, aiding generalisability.

Substitution of the diagnostic MRI machines at our institution from a 1·5 T to a 3·0 T device during the study period was a potential limitation. However, imaging parameters (eg, slice thickness or gap) remained unaltered for all imaging sequences. Moreover, the change in the field strength should not have affected establishment of residual tumour because all patients had preoperative and early postoperative scans taken for direct comparison of contrast enhancement to assess extent of resection. We cannot rule out the systematic error caused by detection of potentially larger volume tumours when scanning with a 3·0 T device than with 1·5 T, because 3·0 T has better display of contrast enhancement;[34] nevertheless, the device change was the same for patients in both treatment groups and probably did not bias outcomes.

Another limitation of our study was the absence of data about patients' quality of life. This outcome needs to be assessed in future, large-scale studies. Furthermore, many patients refused to participate in this study when they learned that there were potential methods of

increasing the extent of resection (eg, use of intraoperative MRI or administration of 5-aminolaevulinic acid) without any obvious negative side-effects, and explicitly requested these options to be used instead.

Moreover, in the intraoperative MRI group, we used a mobile ultra-low-field MRI device, which renders an inferior image resolution compared with high-field systems with field strengths of 1·5 T or 3·0 T. We assume that equivalent results could also be achieved with high-field intraoperative MRI units.

In conclusion, our study shows that intraoperative MRI is an appropriate method to improve the extent of resection of malignant brain tumours, comparable to the use of 5-aminolaevulinic acid. However, whether resection control is best implemented by use of an intraoperative MRI device, or by visualisation of tissue fluorescence after administration of 5-aminolaevulinic acid remains to be seen. We believe that future trials of extent of resection and outcome in brain tumour surgery cannot be undertaken without use of either intraoperative MRI or 5-aminolaevulinic acid as a control.

Contributors

CS, TG, and VS designed the study. CS and VS interpreted the data and drafted the report. AB analysed MRI data. All authors collected data, reviewed the draft, provided comments, and approved the final version of the report.

Conflicts of interest

CS has received honoraria as a speaker from Medtronic Navigation. TG is a member of the scientific advisory board of Medtronic. None of the other authors have any potential conflicts of interests to disclose.

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