Combined Use of Intraoperative Magnetic Resonance Imaging and Neuronavigation for Microsurgical Approach of Intractable Epilepsy:a Systematic Review and Meta-analysis

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Abstract

Introduction

Epilepsy is a major feature of multiple types of lesional epilepsy (LE) and non-lesional (NLE). However, there is an important heterogeneity in the use of such nomenclature. A favorable outcome is correlated to an identifiable cause and the extent of resection. Here, we evaluate the use of intraoperative MRI (iMRI) combined with neuronavigation, in improving the complete and/or adequate resection rates in patients with intractable epilepsy of various etiologies. We further discuss whether this results in better clinical outcomes.

Material and methods

A medical librarian performed a comprehensive review of literature, searching the Medline®, Embase®, Index Medicus® and Cochrane® databases. Two reviewers independently applied following inclusion criteria: reports of at least two cases of any age undergoing microsurgical resection for epilepsy surgery, the use of iMRI as mandatory for intraoperative assessment, evaluation of LE versus NLE, describing if second resection after iMRI was necessary, detailing the extent of resection, qualitative reports of seizure outcome (Engel class).

Results

We report 15 studies, encompassing 867 patients, with various types of LE and NLE. Most common surgical indications for the use of iMRI in LE were dysembrioplastic neuroepithelial tumor (DNET) and gangliogliomas, cavernomas, hypothalamic hamartomas, or primary brain tumors. For NLE these were sclerosis, dysplasia, ischemia and gliosis, which are further separately detailed in a supplementary material. With the use of iMRI, the rate of complete or adequate resection significantly increased from 74.8% (95% confidence interval (CI) 67.3-82.3%) to 97.6% (95% confidence interval (CI) 95.8-99.3%). Hundred and twenty-six cases out of 820 underwent additional resection after iMRI, for an overall rate of 24.4% (range 16.9-31.8). This was translated in an overall clinical benefit with 77.1% (95% CI 71-83.2%) Engel class I at last follow-up ($p<0.001$).

Discussion

Intraoperative MRI might improve the extent of resection in LE and NLE. This might translate into a favorable clinical outcome (Engel class I as high as 77%). This is fairly comparable to what one expects in temporal lobe epilepsy surgery. We suggest that iMRI is beneficial when proposed in selected cases of intractable epilepsy. However, the reader should take into account that such data are not provided by randomized controlled trials and that such conclusions should be carefully interpreted.

Introduction

Epilepsy is a clinical concept that encompasses a heterogeneous group of syndromes, with different etiologies, clinical impact, severity and therapeutic options(1). Epilepsy has been defined conceptually in 2005 as a brain disorder characterized by an enduring predisposition to generate epileptic seizures(2). In a recent systematic review, the point prevalence was 6.38 per 1000 persons, with an annual cumulative incidence of 67.77 per 100.000 persons(3).

Current understanding of natural history, neurobiology and pathophysiology had progressively evolved, further leading to a change in therapeutic approaches(4). Moreover, the understanding of prognostic factors has improved, generating a “prognostic group specific” management that could be explored. In this context, effective treatments may be used in a more rational and targeted fashion(4).

The surgical management is based on type of epilepsy, anatomical location, patient’s preference, as well as surgeon’s expertise(1). Current surgical procedures include resection, disconnection and neural modulation(5). Seizure control rates in patients with focal epilepsy benefiting from surgery ranges between 33–90%(5–10). The former has been improved in recent trials(9, 11) and varies between 80–90% (Engel class I or II(12)) in single and identified MRI structural abnormality (lesional epilepsy, LE) as compared to 36% in non-lesional epilepsy (NLE)(13). Factors associated with good outcome include single unilateral MRI abnormality, localized ipsilateral ictal and interictal epileptiform activity and unilateral hippocampal sclerosis(8, 14). Poor outcome relates to absence of MRI abnormality or multiple MRI abnormalities, bilateral atrophy, suspected cortical dysplasia and non-localizing electroencephalographic (EEG) results(8).

The improvement in neuroimaging and microsurgical techniques has allowed a more specific localization of epileptic foci as well as tailored resections(15, 16). The introduction of frameless stereotaxy further permitted precise craniotomy placement and optimization of the surgical trajectory, avoiding critical structures during intraoperative dissection(17). However, tissue dissection, brain retraction, cerebrospinal fluid loss and gravity often result in brain shift, nullifying preoperative images.

During the past two decades, the development of intraoperative MRI (iMRI) has allowed real-time updating of intracranial neuroanatomy and surgical advancement. Coupled with neuronavigation, it provides real-time valuable information, allowing even more tailored epileptic foci resection, while decreasing morbidity and mortality. However, the use of iMRI in epilepsy varies from center to center in terms of indications, extent of resection, number of controls during surgery in iMRi, surgical outcome etc. Moreover, the benefit of iMRI in epilepsy surgery has not provided level I evidence in terms of safety and efficacy.

Here, we aim at providing a systematic report of studies using iMRI for drug-resistant epilepsy surgery, summarizing the results to date. We further detail its use in both LE and NLE. Our main goal is to provide clinicians with scientifically valid and comprehensible evidence, and to provide estimates of surgical success before and after the use of iMRI in terms of the extent of resection. We further evaluate the clinical outcome at last follow-up in terms of Engel class.

Material And Methods

Data sources

A medical librarian performed a comprehensive review of literature, searching the Medline®, Embase®, Index Medicus® and Cochrane® databases. Moreover, potential studies from systematic reviews were revised in full text to identify relevant articles. We additionally consulted experts and searched for bibliographies on the same topic. In order to benefit from a homogenous dataset, we focused on full-length articles published in English during a 20-years period of time, from January 1999 to December 2019.

Study selection, classification and data screening

The databases were queried using the following word combinations (mesh terms) in the “title” or “title/abstract” item: (“epilepsy” AND “intraoperative” AND “MRI”), or combination of these words, including (“epilepsy” AND “intraoperative” AND “MRI”) etc. We also used the Google Scholar and Google search engine to expand our list of studies, including abstracts, but encompassed in the final analysis only peer-reviewed papers.

Two reviewers (CT, IP) independently applied the following inclusion criteria: a). reports of >=2 cases of any age undergoing microsurgical resection for epilepsy surgery; b). the use of iMRI as mandatory for intraoperative assessment, c). evaluation of LE versus NLE, d). describing if a second evaluation after iMRI was necessary, e). detailing the extent of resection, f). qualitative reports of seizure outcome in terms of Engel class; g). all types of MRI field were included. All included studies reported consistent definitions for both LE and NLE. Moreover, one has to take into account the progressive refinement over time of the MRI techniques and the associated continuous increase of the MR fields in the operative room.

Were excluded studies in other languages than English.

Potentially relevant articles were selected for a full-text screening evaluation, which was independently performed by 3 investigators (CT, IP, NR). Discrepancies were resolved by the corresponding and senior authors (CT, NR).

Data extraction

Were extracted 15 studies(1, 18–31), which included 867 patients (Tables 1 and 2). A flow-chart describing the study selection was created and is displayed in Figure 1. Study characteristics, publication year, sample size, follow-up, anatomical location, LE versus NLE, complete/adequate resection, and second evaluation after iMRI as well as Engel outcome were extracted.

Table 1
Summary of series: basic demographic data

Author (year)	Center (Country)	MR power (T)	Number	Pediatric/ Adult	Demographic details (age, years)	Follow-up	Type of epilepsy	Location	Lesional/ nonlesional	Callosotom
Buchfelder (2000)	Erlangen (Germany)	0.2	61	Both (not specified)	2–60; 32.3 ± 11.9	NA	PharmacoR	Temporal resection & callosotomy	29/28	n=4
Buchfelder (2002)	Erlangen (Germany)	0.2	58	5/53	2–60; 33 ± 12	mean: 15.5 lesional, 10.7 non-lesional	PharmacoR	Temporal resection	29/28	No
Kaibara (2002)	Calgary (Canada)	1.5	14	0/14	23-55; 36 ± 10	median: 17 ± 3.4	PharmacoR	Temporal resection	0/14	No
Schwarz (2002)	(New Jersey, USA)	0.12	5	3/2	7-65	mean: 9.2	PharmacoR	Temporal resection	1/4	No
Walker (2002)	Boston (USA), Brisbane (Australia)		13	2/13	26.1 years (range 5±40)	mean 22.1 months (range 2±48)	PharmacoR	Temporal and other	0/11	No
Kelly (2005)	Calgary (Canada)	1.5	70	11/59	33 ± 13	>6	PharmacoR	Temporal and other	9/58	n=3
Sun (2011)	Beijing (China)	1.5	36	4/32	10-56; 32.78 ± 12.92	mean: 12.6	9/36 PharmacoR	Eloquent areas, mixed	36/0	No
Sommer (2013)	Erlangen (Germany)	1.5	25	2/23	12-67; mean 37	median: 44.2 ± 26.9	PharmacoR	Extratemporal	9/16	No
Kurwale (2015)	New Delhi (India)	1.5	39	Both (not specified)	3-65; mean 22	mean: 14	PharmacoR	Mixed	12/27	No
Sommer (2015)	Erlangen (Germany)	1.5	69	Both (not specified)	28.5 ± 15.4	median: 55.5 ± 36.2	51/69 PharmacoR	Mixed	69/0	No
Warsi (2016)	Montreal (Canada)	3	39	39/0	0-18; mean 8	>24	PharmacoR	Mixed	12/27	No
Sacino (2016)	(Washington, USA)	1.5	12	12/0	0-18; 8.8 ± 1.6	mean: 3.5	PharmacoR	Mixed	0/12	No
Roessler (2016)	Erlangen (Germany)	1.5	415	Both (not specified)	5-69; mean 37.2	36; range 3-10.8 y	PharmacoR	Mixed	112/177/other non specified	No
Sacino (2016)	(Washington, USA)	1.5	11	11/0	9.1 ± 2.0	5.72; range 0.46–10.61 months	PharmacoR	Mixed	0/11	No
Van Tonder (2018)	Liverpool (UK)		10	10/0	7 y (range 2-17 y).	mean 34 months, 1–76 months	PharmacoR	Extratemporal, HH	10/0	No
Total numbers			867	99 Pediatric 196 Adult (if reported)					320 Lesional 413 Non lesional (if reported)	

Table 2
Summary of series: final diagnosis, complete/adequate resection, surgical outcomes in terms of Engel class I

Author (year)	Number	Anatomopathological diagnosis (lesional)	Anatomopathological diagnosis (nonlesional)	Complete/adequate resection (after 1st iMRI)	Second evaluation after iMRI	Engel class I
Buchfelder (2000)	61	Pilocytic astrocytoma (2), Astrocytoma grade II (9), gangliogliomas (4), DNET (2), cavernoma (8), other (4)	Sclerosis (9), cortical dysplasia (2), gliosis (12), cortical microdysgenesis (3), glioneural hamartia (2), no abnormality (4)	55/61 (90%)	3/61 (4.9%)	46/61 (75%)
Buchfelder (2002)	58	Pilocytic astrocytoma (6), astrocytoma grade II (4), gangliogliomas (2), DNET (2), cavernoma (7), other (8)	Sclerosis (10), dysplasia (3), gliosis (7), other (9)	53/58 (91.3%)	3/58 (5.2%)	47/58 (81%)
Kaibara (2002)	14	NA	Sclerosis (4), heterotopia (1), other/normal (9)	7/14 (50%)	7/14 (50%)	13/14 (92.8%)
Schwarz (2002)	5	DNET (1)	Sclerosis (3), dysplasia (1)	0/5 (0%)	5/5 (100%)	5/5 (100%)
Walker (2002)	13	Gangliogliomas (5), DNET (3), HH (1)	Cortical dysplasia (4)	8/13 (61.5%)	5/13 (39.5%)	4/13 (30.7%)
Kelly (2005)	70	51 (73%) TLE Gangliogliomas (4), DNET (2), other (3)	Sclerosis (39), dysplasia (9), other (10)	51/70 (72.8%)	18/70 (25.7%)	41/70 (58.5%)
Sun (2011)	36	Cavernoma (36)	Cavernoma	36/36 (100%)	0%	17/20 (85%)
Sommer (2013)	25	Gangliogliomas (2), DNET (2), Cavernoma (5)	Dysplasia (7), gliosis (5), other (4)	20/25 (80%)	5/25 (20%)	19/25 (76%)
Kurwale (2015)	39	Pilocytic astrocytoma (2), DNET (4), hamartoma (3); other (3)	Sclerosis (7), dysplasia (11), gliosis (9)	30/39 (77%)	5/39 (12.8%)	33/39 (84.6%)
Sommer (2015)	69	Gangliogliomas (69)	N/A	33/48 (68.7%)	9/48 (18.7%)	42/60 (70%)
Warsi (2016)	39	Tumor (no details, 11), cavernoma (1)	Sclerosis (3), dysplasia (12), ischemia (8), other (4)	32/39 (82%)	7/39 (21.8%)	34/39 (87.1% Engel I and II included together)
Sacino (2016)	12	NA	Dysplasia (12)	7/12 (58.3%)	5/12 (41.6%)	11/12 (91.6%)
Roessler (2016)	415	LEAT (GG, DNET- 67), cavernoma (45)	Sclerosis (146), dysplasia (31)	369/415 (89%)	46/415 (11%)	272/374 (72%) with complete follow-up
Sacino (2016)	11	NA	Dysplasia (11)	7/11 (63.6%)	4/11 (36.3%)	9/11 (82%)
Van Tonder (2018)	10	Hypothalamic hamartoma	Hypothalamic hamartoma (10)	6/10 (60%)	4/10 (40%)	8/10 (80%)
Lesional: Pilocytic astrocytoma= 10, astrocytoma grade II= 13, DNET= 16, Gangliogliomas = 84, DNET+Gangliogliomas= 167, HH= 14, Cavernoma = 102 and Other= 18						
Nonlesional: Sclerosis= 221, Dysplasia= 103, Gliosis= 33, Cortical microdysgenesis= 3, Glioneural hamartia= 2, No abnormality= 4, Ischemia= 8, Other= 40						

The data extraction for NLE only is presented in the supplementary materiel.

Terminology issues

In order to respect definitions reported by authors of included studies, two groups were analyzed: LE and NLE.

Lesional epilepsy was constantly defined as related to easily detected and well-defined pathologies on MRI: tumors (i.e. pilocytic astrocytoma, astrocytoma, DNET, gangliogliomas, DNET+gangliogliomas), cavernous malformations etc.

Intractable epilepsy is however frequently related to other types of pathology, where the epileptic focus and epileptogenic zone can become subtler or poorly defined on cerebral MRI. Such pathologies include sclerosis, dysplasia, gliosis, cortical microdysgenesis, glioneural hamartia, ischemia etc. This group has

consistently been reported as NLE. Of note, no visible abnormality on preoperative MRI was included in this group.

Statistical analysis

Weighted summary rates were determined using meta-analysis models. The test for heterogeneity was performed for each meta-analysis. In cases of heterogeneity, a binary random-effects model (DerSimonian-Laird method) was used in some of the analysis assuming that the included studies were a random sample from hypothetical population; otherwise, a binary fixed-effects model with inverse variance weighting was employed.

We used OpenMeta (Analyst) from the Agency for Healthcare Research and Quality to perform our analyses. Pooled estimates using meta-analytical techniques were obtained for the outcome of complete/adequate resection before and after using iMRI, as well as for Engel class I outcome (when reported separately), which followed binomial distributions.

Results

Populations

The mean follow-up periods as well as the basic demographic data are reported in Table 1.

Of note, pediatric cases were exclusively reported by four studies(23, 28, 30, 31), comprising 72 cases. All the others described both adult and pediatric cases in different proportions.

The results for NLE only are presented in the supplementary materiel.

Surgical indications

Overall number of cases reported for LE was 320 and for NLE was 413 patients(1, 18–31) (cases where individual clear anatomopathological diagnosis was specified).

Most common surgical indication in LE (figure 2, upper part) was dysembrioplastic neuroepithelial tumor (DNET) and gangliogliomas (n=167), cavernomas (n=102), gangliogliomas (n=84), DNET (n=16), HH (n=14), WHO grade II astrocytoma (n=13) and pilocytic astrocytoma (n=10)(1, 18–31). In NLE this frequently included (figure 2, lower part) sclerosis (n=221), dysplasia (n=103), ischemia (n=8) and gliosis (n=33)(1, 18–31).

Pediatric studies reported mainly surgery for tumor, cavernomas and hypothalamic hamartomas (HH) or dysplasia, ischemia, sclerosis and other causes(23, 28, 30, 31).

Complete or adequate resection based on initial preoperative neuroimaging assessment

Pooled overall initial complete or adequate resection rate was 74.8% (95% confidence interval (CI) 67.3-82.3%). A binary random-effects model was used ($p < 0.001$, $I^2 = 88.84$).

Further intervention after iMRI

Hundred and twenty-six cases out of 820 underwent additional resection after iMRI, for an overall rate of 24.4% (range 16.9-31.8). A binary random-effects model was used ($p<0.001$, $I^2 = 85.32$, figure 3, Table 3).

Table 3
Summary of series: complications, need for reintervention, main message

Author (year)	Number	Complications	Engel class I :	Surgical indications for reintervention	Main results and/or message
Buchfelder (2000)	61	-	38/61 (62.3%)	3/61 (4.9%)	A second look (n=3) could increase the rate of total resection in the lesional cases from 79–90%. iMRI allowed evaluating the extent of resection and/or disconnection.
Buchfelder (2002)	58	LE: 4/29 (13.8%) NLE: 9/29 (31%)	LE: n=22/29 (75.9%) NLE: n=17/29 (58.6%)	LE: n=2 NLE: n=1	Gliomas total resection rate: 73% -> 87%; extension in eloquent areas precluded TR Overall: 16% postoperative changes in resection volume
Kaibara (2002)	14	1/14 (7.1%)	13/14 (93%)	7/14 (50%)	In TLE, iMRI can identify residual mesial temporal lobe targets before craniotomy closure.
Schwarz (2002)	5	0/5 (0%)	5/5 (100%)	-	iMRI is an useful adjunct for surgical treatment of MTLE, and perhaps the most reliable method of standardizing a complete hippocampectomy.
Walker (2002)	13	2/13 (15.4%)	5/13 (38.5%)	5/13 (38.5%)	iMRI is a safe and effective adjunct for the surgical treatment of benign intracranial lesions presenting with seizures.
Kelly (2005)	70	1/70 (1.4%)	LE: n=7/7 (100%) NLE: n=34/59 (57.6%)	LE: n=3 NLE: n=15	Benefit in patients with cortical dysplasia. Decrease likehood of distant reintervention in TLE.
Sun (2011)	36	0%	LE: 7/9 (78%)	2 patients with further resection in extratemporal location	Supratentorial cavernomas in eloquent brain areas. Sparing parts of the surrounding hypointense rim in 10 patients to prevent deficits.
Sommer (2013)	25	Transient 20% Permanent 12%	72% (all lesional)	20%	Benefit in patients with extratemporal epilepsies close to eloquent areas (distance less than 20 mm). Improved clinical outcomes. Could potentially avoid awake surgery.
Kurwale (2015)	39	4/39 (10.3)	77%	4 lesions on eloquent area or less than 1 mm apart	In LE, iMRI modified operative strategy resulting in increase resection in 5/23 (21%). In LE, iMRI increased the extent of resection.
Sommer (2015)	69	Transient 1 (1.4%) Permanent 4 (5.8%)	42/60 (72%)	Remnant tumor in 28%	In GG surgery, the authors raised the rate of complete resection by 19%. Remnant tumor identified using iMRI in 13/46 (28%).
Warsi (2016)	39	2/39 (5.1%)	34/39 (87.2%) Engel I and II reported together	-	Retrospective analysis with and w-iMRI: Engel I/II outcome more frequent in iMRI. At 2-years similar results. Does not favor iMRI in pediatric epilepsy.
Sacino (2016)	12	-	11/12 (92%)	5/12 (42%)	iMRI precluded the need for repeat surgery in pediatric patients with focal cortical dysplasia.
Roessler (2016)	415	16.3%	72.7%	49/415 (1.8%)	Increased likelihood of Engel I found in cavernoma, followed by hippocampal sclerosis and long-term epilepsy-associated tumor. Higher resection volume associated with a higher chance of favorable seizure outcome, especially in long-term epilepsy-associated tumor or diffuse gliomas.
Sacino (2016)	11	4/11 (36%)	9/11 (82%)	4/11 (36%)	For resection of lesions in peri-eloquent cortex, the incorporation of iMRI led to elevated rates of gross total resection and postoperative seizure freedom.
Van Tonder (2018)	10	0/10 (0%)	8/10 (80%)	4/10 (40%)	In HH, iMRI can be used to tailor the ideal tumor resection based on the anatomy of the lesion.

Complete or adequate resection based on iMRI with further intervention

Pooled overall complete or adequate resection rate after iMRI use was 97.6% (95% confidence interval (CI) 95.8-99.3%). A binary random-effects model was used (p= 0.003, I^2= 56.852, figure 3, Table 3).

Clinical outcome in terms of Engel class I at last follow-up

Pooled overall Engel class I at last follow-up was 77.1% (95% confidence interval (CI) 71-83.2%). A binary random-effects model was used (p< 0.001, I^2= 68.134, figure 4).

Discussion

In the present meta-analysis, we report 15 studies, encompassing 867 patients, with various types of LE and NLE. Most common surgical indications in LE were dysembrioplastic neuroepithelial tumor (DNET) and gangliogliomas included together or separately, cavernomas, HH, or primary brain tumors and in NLE were sclerosis, dysplasia, ischemia and gliosis. With the use of iMRI, the rate of complete or adequate microsurgical resection significantly increased from 74.8% (67.3-82.3%) to 97.6% (95.8-99.3%). This was translated in an overall clinical benefit of Engel class I at last follow-up of 77.1% (71-83.2%). While this meta-analysis included various types of epilepsy, the favorable clinical outcome is fairly comparable to what one would expect in temporal lobe epilepsy (TLE), which is universally considered to have the best postoperative seizure control.

The surgical aim of resective epilepsy surgery is either complete excision or disconnection of the epileptic network, with preservation of eloquent cortex(32). In order to achieve this, presurgical correct diagnosis is mandatory. Modern epileptologists can use multimodal diagnostic tools, including semiology analysis, electrophysiological recordings, functional testing and complex neuroimaging techniques(32). All these remain complementary and should define the location and boundaries of the epileptic zone. In challenging cases, stereo-electroencephalography (SEEG) by depth electrodes is considered of major help for evaluation and tailored navigated resection, even in patients with non-lesional or extratemporal focal epilepsy(33). In fact, it has been already acknowledged that presence of a lesion does not necessarily correlate with an epileptogenic network solely driven by that particular lesion. Moreover, a lesion itself can recruit and further drive other epileptogenic zones in the brain, making diagnosis even more challenging(34, 35). The clinical aim of resective epilepsy surgery remains the best possible seizure control, while experiencing the least possible neurologic or neuropsychological impairment. This is achieved by a maximized resection, which is mandatory for good seizure outcome.

Surgically accessible pathologies associated with medically refractory epilepsy often include hippocampal sclerosis, long-term epilepsy-associated tumors, cavernous malformations or focal cortical dysplasia(36, 37). Presence of a visible lesion on MRI correlates with better postsurgical outcomes, as does complete surgical excision of such lesions(38, 39). In contrast, intrinsic epilepsy-associated tumors might have diffuse borders and less accessible anatomical locations, such as adjacent to motor or speech areas(22, 25).

Optimal resection goals are mostly attained in temporal locations, translating into good surgical outcomes as opposed with those in extratemporal ones(27). In a recent meta-analysis(40) on long-term postsurgical outcomes seizure freedom was reported in 64% of TLE and only 34% in extra TLE, particularly for cortical malformations. Of note, one of the important reasons was incomplete removal, due to proximity to eloquent motor areas and white matter tracts. In this context, iMRI can be a valuable therapeutic adjunct, together with neuronavigation. Its utility should be seen in the context of the specific pathology related to medically intractable seizures. In TLE, iMRI can document the extent of mesial and neocortical resections as alternative to classical tailored anterior or posterior temporal lobe resections rather than standard lobectomy in attempt to maximize preservation of adjacent parenchyma(18).

In extra TLE, a variety of histopathological findings can be identified. Not all of them are necessarily well defined on neuroimaging (in contrast to hippocampal sclerosis for example). Some are further located near functional cortex or fiber tracts and thus are not necessarily amenable to complete resection without neurological impairment(25). Combined with BOLD and tractography, iMRI can offer a higher extent of resection. It can further compensate the brain shift and can adjust inaccuracy of coregistration, improve functional mapping and fiber tracking.

In cortical dysplasia, the concept of seizure outcome as related to extent of resection is also applicable. iMRI can be a valuable tool, as it is often more subtle and difficult to visually differentiate cortical dysplasia from normal brain parenchyma, in terms of intraoperative macroscopic aspects(1), causing even in the experienced neurosurgeon a feeling of false complete resections(21).

Limitations

One of the limitations is the retrospective nature of the included studies, the small sample size of each of them, as well as the lack of randomized controlled trials. A second limitation is the use of multiple surgical procedures, depending on the main pathology, inside the same report. A third limitation is that not all studies included the complete spectrum of pathologies. A fourth limitation is that we cannot comment on the surgeon's personal insight, leading to the decision-making. A fifth limitation is related to a potential selection bias of choosing the microsurgical approach, while including iMRI in the surgical armamentarium. Moreover, there was a progressive increase in the iMRI field during time; as such, our results have to be balanced with the constant evolution of intraoperative technologies. Only one study included in the present meta-analysis used 3 T iMRI. An open question is what should be the minimum postoperative follow-up in these cases (e.g. 12 months?). A technical limitation can be related to errors during calculation of functional data, target registration of the navigation systems, registrations between pre- and postoperative MRI etc. As an alternative for iMRI and neuronavigation, in selected cases, awake craniotomy represents a valuable option in experienced centers(47). A further limitation relates to specific terminology of what some authors consider as LE, while other as NLE. A last, yet important limitation, is the lack of randomized controlled trials, which would increase the level of evidence.

Conclusions

Intraoperative MRI provides an update in terms of neuroimaging during general anesthesia with the patient positioned for surgery. Combined with functional neuronavigation, it helps in evaluating the extent of resection, change or adapt the surgical plan, while correcting for brain shift, and potentially evaluates the presence of intraoperative complications. Initial extent of resection can sometimes be overestimated. In this sense, the present review suggests higher complete/adequate resection rates after performing an iMRI. When taking advantage of this recent technological innovation, the rate of complete or adequate resection might increased from an overall rate of 74.8–97.6%. This could potentially translate in an overall clinical benefit of Engel class I at last follow-up of

77.1%. In the largest reported series of the present meta-analysis, increased likelihood of Engel I was found in cavernoma, followed by hippocampal sclerosis and long-term epilepsy-associated tumor. However, the reader should take into account that such data are not provided by randomized controlled trials and that such conclusions should be carefully interpreted.

Incorporating surgical robots will increase surgical precision and accuracy, allowing precise removal and potentially further modulation of abnormal tissue. Randomized controlled trials are necessary to evaluate the real impact of such new technologies.

Declarations

Conflict of interest:

none

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Disclosures:

none as related to the present manuscript and topic

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Figures

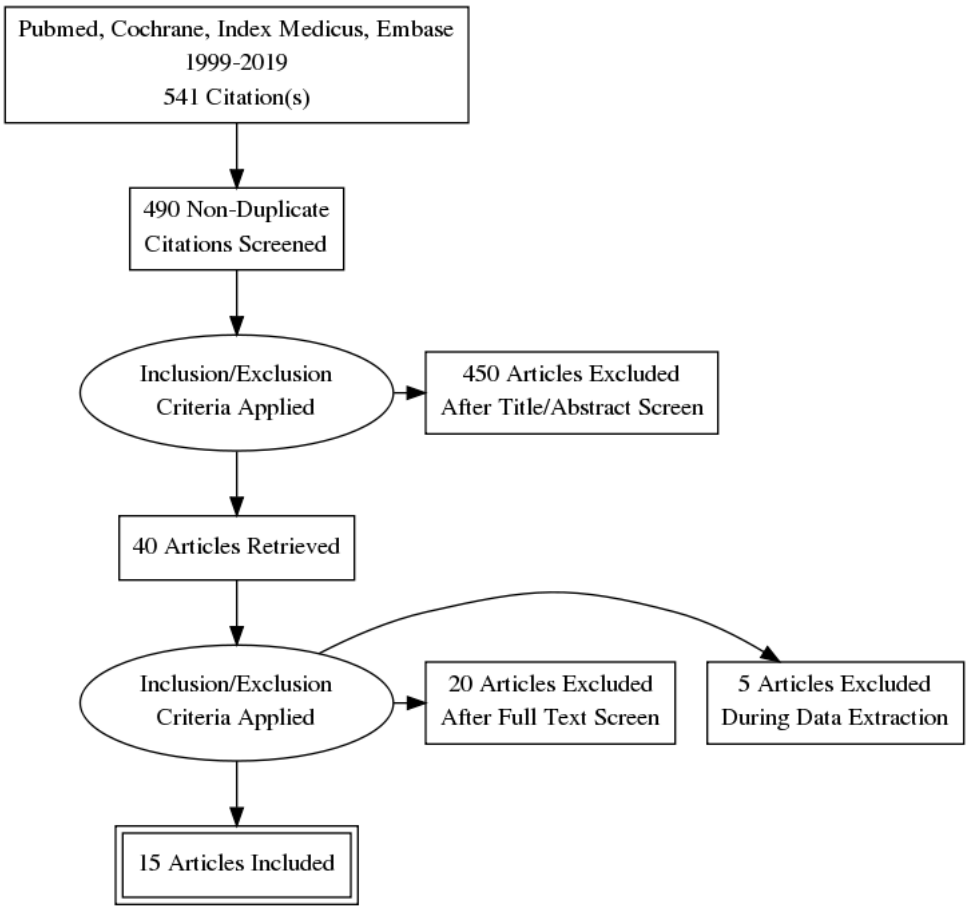

Figure 1

Prisma flow diagram describing the study selection

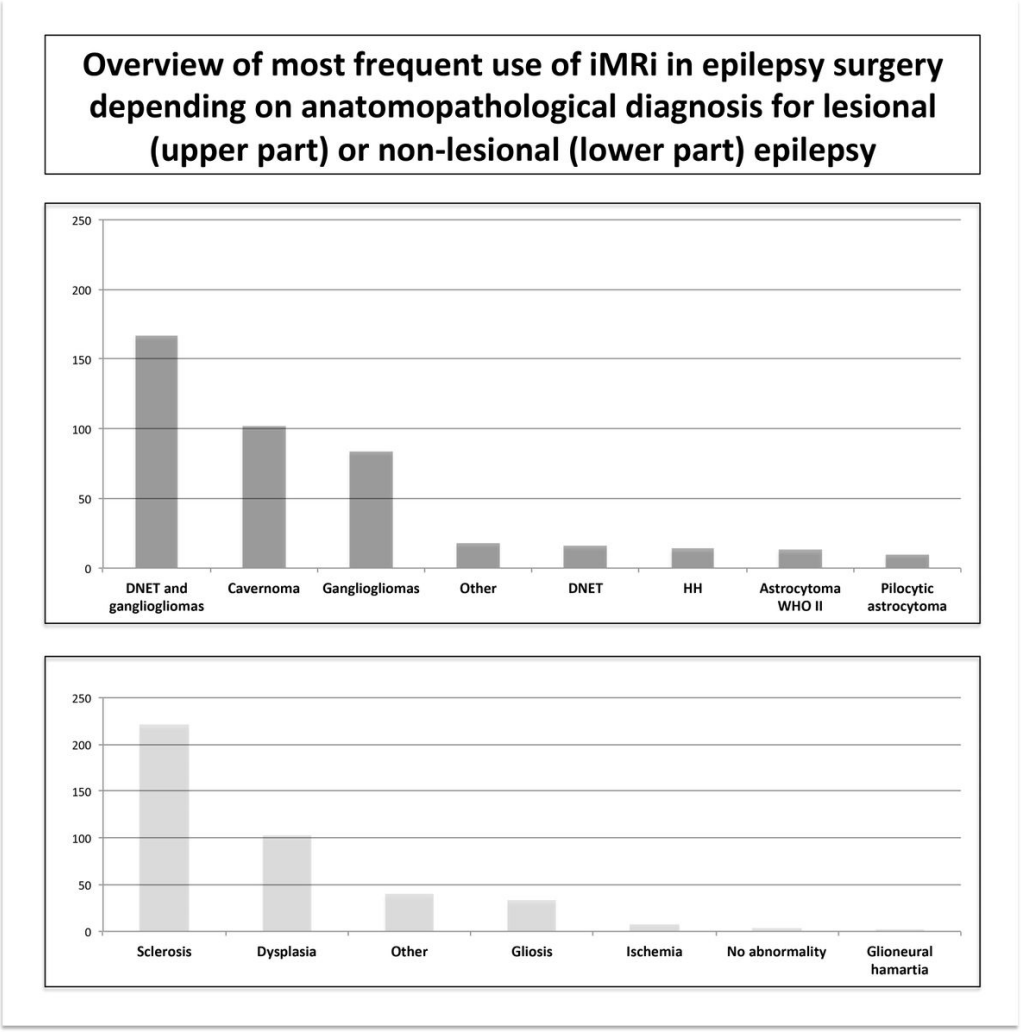

Figure 2

Overview of the most frequent use of iMRI in epilepsy surgery depending on the anatomopathological diagnosis for lesional (upper part) and non-lesional (lower part) epilepsy

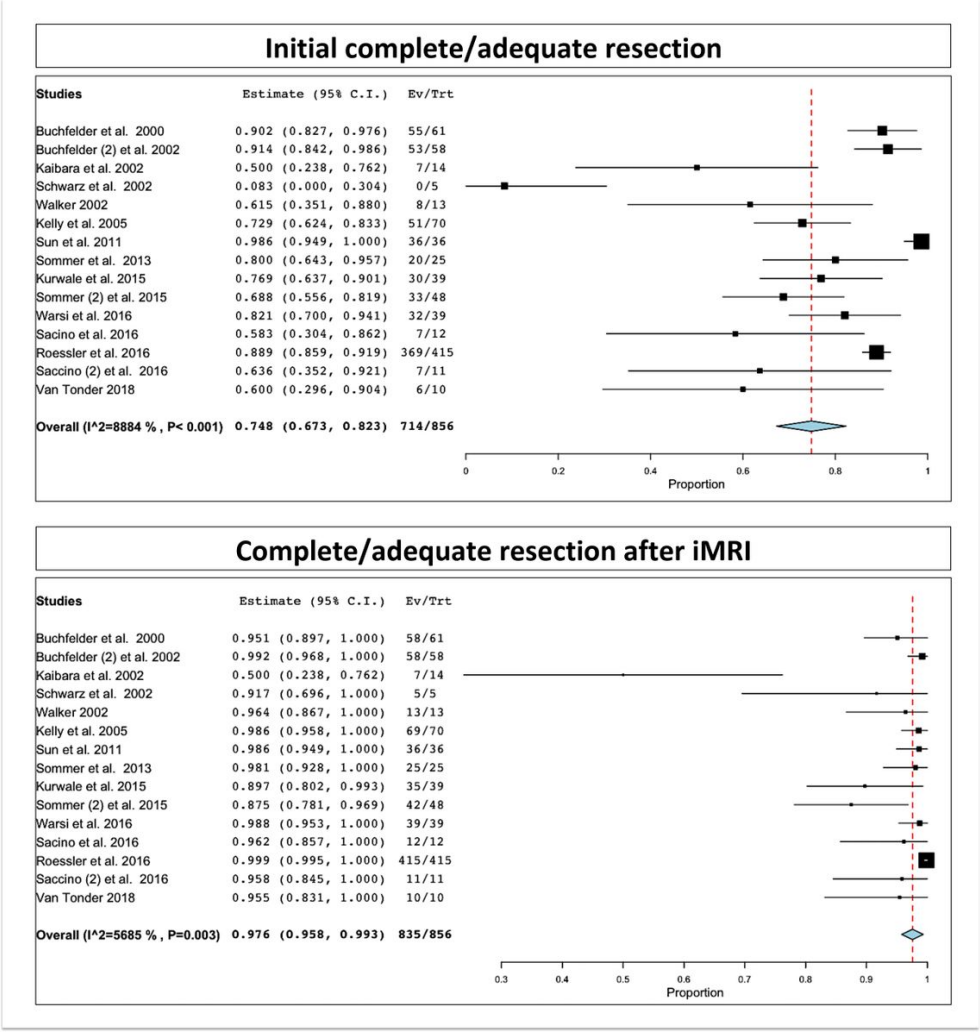

Figure 3

Initial complete/adequate resection rates before intraoperative MRI use (upper part); complete/adequate resection rates after intraoperative MRI use (lower part)

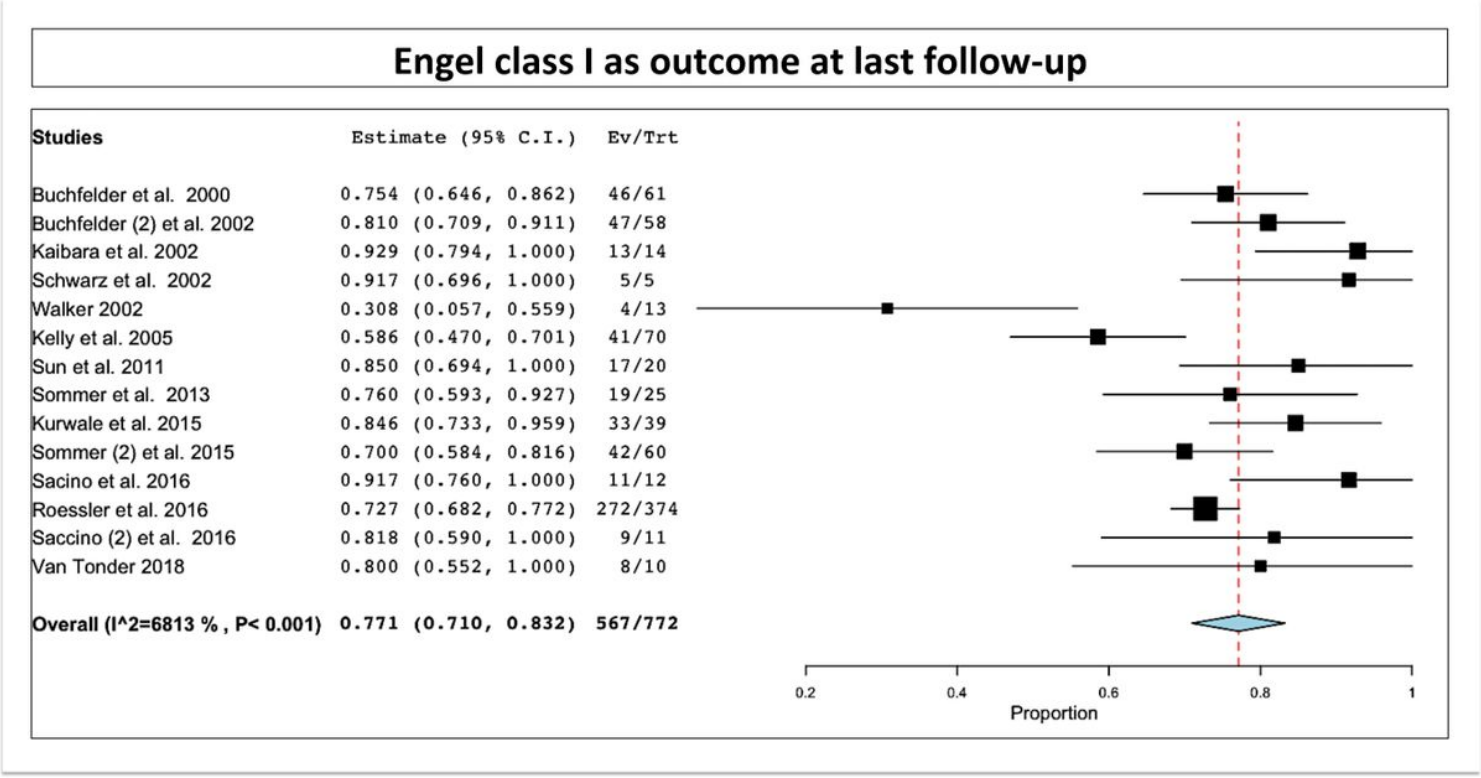

Figure 4

Engel class I as outcome at last follow-up

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