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Clinical safety of intracranial EEG electrodes in MRI at 1.5 T and 3 T: a single-center experience and literature review

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Abstract

Purpose Intracranial electroencephalography (EEG) can be a critical part of presurgical evaluation for drug resistant epilepsy. With the increasing use of intracranial EEG, the safety of these electrodes in the magnetic resonance imaging (MRI) environment remains a concern, particularly at higher field strengths. However, no studies have reported the MRI safety experience of intracranial electrodes at 3 T. We report an MRI safety review of patients with intracranial electrodes at 1.5 and 3 T.

Methods One hundred and sixty-five consecutive admissions for intracranial EEG monitoring were reviewed. A total of 184 MRI scans were performed on 135 patients over 140 admissions. These included 118 structural MRI studies at 1.5 T and 66 functional MRI studies at 3 T. The magnetic resonance (MR) protocols avoided the use of high specific energy absorption rate sequences that could result in electrode heating. The intracranial implantations included 114 depth, 15 subdural, and 11 combined subdural and depth electrodes. Medical records were reviewed for patient-reported complications and radiologic complications related to these studies. Pre-implantation, post-implantation, and post-explantation imaging studies were reviewed for potential complications.

Results No adverse events or complications were seen during or after MRI scanning at 1.5 or 3 T apart from those attributed to electrode implantation. There was also no clinical or imaging evidence of worsening of pre-existing implantation-related complications after MR imaging.

Conclusion No clinical or radiographic complications are seen when performing MRI scans at 1.5 or 3 T on patients with implanted intracranial EEG electrodes while avoiding high specific energy absorption rate sequences.

Keywords Clinical safety · Intracranial electrodes · Magnetic resonance imaging

Introduction

Intracranial video-electroencephalography (EEG) monitoring is routinely performed in the presurgical assessment of patients with drug resistant epilepsy [1]. Placement of intracranial EEG (iEEG) electrodes is guided by previous investigations (e.g., scalp video-EEG monitoring, magnetic resonance imaging [MRI], PET, and SPECT) [2]. A critical step in intracranial monitoring is the confirmation of electrode placement and identification of any complications of electrode implantation by diagnostic imaging. Complications related to intracranial electrode implantation include post-operative edema, extra-axial collections, intracranial hemorrhage, and hardware-related complications such as fractured electrodes [3]. Recently, a meta-analysis showed a 1.3% and 3.5%

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overall complication rate for depth and subdural/depth electrode implantation, respectively [4].

In the past, skull X-rays and cranial computed tomography (CT) have been used to confirm electrode placement and to identify any complications related to implantation [5, 6]. However, MRI is being increasingly used to confirm electrode placement due to its superior spatial resolution and tissue visualization. The use of MRI also circumvents radiation exposure associated with CT. Lastly, MRI can readily identify complications related to electrode implantation. Indeed, post-implantation complications such as electrode tract hemorrhage are less apparent in CT images than MR images due to extensive streak artifacts associated with CT scanning.

Despite these advantages, there are potential risks associated with magnetic resonance (MR) scanning in this context. These risks include thermal injury due to absorption of radiofrequency energy, mechanical displacement of electrodes, and induced electric currents related to switching magnetic fields [7]. Although there are reports of adverse events (including permanent neurological deficits) related to MR scanning with implanted deep brain stimulation hardware at 1.0 or 1.5 T [8, 9], no adverse events have been reported from scanning patients with implanted iEEG electrodes.

Because the safety of MRI in patients with iEEG electrodes is of utmost importance, phantom safety studies have been performed at 1.5 and 3 T prior to human scanning [7, 10, 11]. Subsequent to this, three iEEG-functional magnetic resonance imaging (fMRI) human studies at 3 T involving 15 patients from our center [12–14] and four iEEG-fMRI studies involving six patients at 1.5 T have been published to date [15–18]. However, these studies did not focus on MR safety. Thus, to the best of our knowledge, there are no reports of the safety experience or complications related to MRI scanning of patients with implanted iEEG electrodes at 3 T. Importantly, in 2019, one of the main manufacturers of iEEG electrodes (Ad-Tech, Racine, WI, USA) recalled supplemental information regarding the MRI safety of their subdural and depth electrodes as well as anchor bolts. Therefore, we report our safety experience related to 1.5 and 3 T MRI performed in patients with implanted iEEG electrodes.

Methods

Subjects

One hundred and sixty-five consecutive admissions for adult and pediatric patients for iEEG video monitoring at the University of Calgary Comprehensive Epilepsy Centre were reviewed between February 2011 and February 2020. All patients underwent structural MRI at 1.5 T and/or an intracranial EEG-fMRI study at 3 T, which included structural MR image acquisition. Some patients also underwent post-implantation CT scans either prior to or after MRI scanning. Note that all 1.5 T MR and CT scans in children and adults were obtained entirely for clinical purposes to confirm electrode placement. On the other hand, all 3 T scans were obtained in adults (> 18 years) as part of ongoing intracranial EEG-fMRI studies at our center. The study was approved by Conjoint Health Research Ethics Board, University of Calgary. Written informed consent was obtained from all patients.

Intracranial EEG

Commercially available platinum subdural strip, subdural grid, or depth electrodes were used in all patients (Ad-Tech, Racine, WI). The most commonly used electrodes were 10 contact strip (TS10R-SP10X-000), 32 contact grid (FC32C-SP10X-000), and 8 contact depth (SD08R-SP10X-000). The electrodes were implanted according to clinical need and following standard protocols at our epilepsy center. Subdural strip and grid electrodes were inserted through burr holes or craniotomies. Depth electrode implantation was performed stereotactically using a Leksell frame or robotic stereotactic assistance (ROSA) using varying combinations of 4-, 6-, 8- or 12-contact electrodes [19] often with the use of titanium anchor bolts.

Image acquisition

MRI at 1.5 T

Limited sequences that avoid high specific absorption rates were used to confirm electrode placement. These included an axial 3-mm thick T2* GRE and an axial 1-mm thick 3D T1-weighted volumetric sequence with multiplanar reformats (anatomical 2D T2* GRE: TE = 17.6 ms, TR = 631 ms, flip angle = 25°, 256 × 140 matrix, 34 × 4-mm thick slices; anatomical 3D T1-weighted: TE = 3.37 ms, TR = 1900 ms, flip angle = 15°, inversion pulse 1100 ms, 256 × 256 matrix, 160–176 slices 1 × 1 × 1 mm). These were performed using a Siemens 1.5 T Avanto Fit (Erlangen, Germany) or 1.5 T GE Optima GEM Suite (Waukesha, USA) scanner equipped with a transmit/receive coil, following a standard protocol used for all patients at our medical center.

iEEG-fMRI at 3 T

Safety testing at 3 T was previously performed at our center using a phantom head model with a full iEEG-fMRI protocol prior to use in patients [7]. Details of our human 3 T iEEG-fMRI protocol can be found in previous publications [12–14]. The first seven patients were scanned using a 3 T GE Signa LX whole-body scanner with a receive-only eight-channel phased-array head-receive/body-transmit coil, while the remaining patients were scanned using a 3 T GE Discovery

MR750 whole-body scanner with an eight-channel receive-only phased-array head coil (GE Healthcare, Waukesha, WI). Subjects were closely monitored by a physician while undergoing the study and after the study while they were still in hospital.

EEG electrode tails were attached to custom-modified electrode connectors capable of recording up to 64 contacts (L-SRL-10DIN, Ad-Tech, Racine, WI). Safety resistors were present in the connecting cables to limit any induced currents. The cable lengths were constant between patients, and shorts were avoided. In some patients, there were more EEG electrodes than connectors, in which case, the open tails were covered by short pieces of plastic tubing. The electrode connectors were led out the front of the MR scanner along the right or left side of the patient, depending on the location of the implanted EEG electrodes. At the foot of the table, these connectors were attached to a commercial 11.8-m copper connecting cable (Compumedics Neuroscan, Charlotte, NC, USA) which led out of the scanner room through a waveguide into the MR console room, where it was connected to a commercially available 64 channel MR-compatible EEG system (SynAmps RT MagLink, Compumedics Neuroscan, Charlotte, NC).

The MR imaging protocol included multi-slice anatomical imaging (spoiled gradient-recalled echo 2D multi-slice sequence: TE = 2.1 ms, TR = 150 ms, flip angle = 18°, 128 × 128 matrix, 24 5.00-mm thick slices; anatomical 3D T1-weighted imaging: TE = 3.8 ms, TR = 9.3 ms, flip angle = 12°, 24-cm field of view, 320 × 256 × 64 matrix, 0.47 × 0.47 × 2.00-mm thick slices). In addition, fMRI was performed (spoiled gradient recalled echo planar imaging: TE = 30 ms, TR = 1500 ms, flip angle = 65°, 24-cm field of view, 64 × 64 matrix, 24 slices 3.75 × 3.75 × 5.00 mm).

The iEEG-fMRI studies were performed toward the end of each patient's hospital admission, usually within 24 h of electrode explantation. Most subjects were scanned for one to three consecutive 20-min runs, each comprising 800 3D volumes. Although the total planned length of fMR image acquisition was 60 min, some studies ended sooner due to either expiration of the scheduled scanning session or patient discomfort (e.g., sore back or neck).

Literature search

An online PubMed and Medline search of literature in English was performed on 19 September 2019. The search parameters used were ("magnetic resonance imaging" or "MRI" or "functional MRI") and ("safety" or "adverse event" or "patient harm" or "patient safety" or "complication") and ("implanted electrodes" or "intracranial electrodes" or "subdural electrodes" or "depth electrodes" or "intracerebral electrodes" or "subdural grids" or subdural strips"). Publications on safety and those mentioning complications associated with intracranial electrodes in the MRI environment including phantom, animal, and human studies were selected irrespective of the type of EEG electrode used. Studies pertaining to deep brain stimulation electrodes were not included because the focus of the present study was intracranial EEG recording electrodes.

Safety review

The literature search was used to provide information on safety data to be sought in the clinical records and images that were reviewed. Records reviewed included inpatient medical records, discharge summaries, as well as MRI and CT reports of scans performed after electrode implantation and after electrode explantation. In addition, all images were reviewed by JNS, a board-certified neuroradiologist with more than 17 years of experience in epilepsy imaging.

Known complications of EEG electrode implantation were first reviewed. This included monitoring for symptoms such as mild to moderate headache, mild skin tenderness at depth electrode entry points, nausea, and neck stiffness [20]. These symptoms gradually resolve over several days. MRI and CT scans were reviewed for evidence of pneumocephalus and extra-axial collections which are potential complications of subdural strip and depth electrode implantation [21]. Imaging evidence of known complications of depth electrode implantation was also sought. This evidence included small, asymptomatic electrode tract hemorrhages that did not require intervention as well as transient mild asymptomatic focal edema [19]. All of the aforementioned complications related to electrode implantation were identified as being "expected."

Known transient self-limited symptoms associated with MR scanning itself (without implanted devices) were also monitored and identified as being "expected." These symptoms included mild nausea, headache, vertigo, tingling, and tapping sensations due to peripheral nerve stimulation [22]. Because of the longer scanning time of the iEEG-fMRI study (~ 60 min), self-limited symptoms such as back and neck discomfort as well as mild sensations of head warmth were also expected and documented.

Although our literature review did not reveal any reports of adverse events specifically related to MRI scanning with implanted EEG electrodes in humans, potential complications were identified based on data available from phantom and animal safety studies as well as human adverse events seen with deep brain stimulation hardware [8, 9]. The potential complications that were monitored included (i) new or worsening of pre-existing focal neurological deficits resulting from electrode heating or device movement which could lead to tissue damage/edema/hemorrhage, (ii) headaches resulting from heating or stimulation of the dura, (iii) positive motor or sensory transient neurological symptoms from inadvertent neurological stimulation due to varying magnetic fields (e.g.,

muscle twitches, involuntary movements, and nasal bridge sensations) which have been previously reported with deep brain stimulation hardware [9, 23], or (iv) any other new symptom or imaging finding. If a patient reported new neurological symptoms, the tissue near the presumed anatomical substrates for the symptoms was carefully reviewed.

Any expected or unexpected symptoms reported by the patient during or after MRI scanning (1.5 T or 3 T) were retrieved from their medical records and discharge summary. All available imaging reports and images (CT, 1.5 T or 3 T MRI) were also reviewed looking for any evidence of tissue damage related to scanning at 1.5 T or 3 T. This evidence included electrode displacement as well as thermal injury or hemorrhage adjacent to any electrode or along any depth electrode tract. Note that the images and reports that were reviewed included those from the MRI study itself as well as any follow-up scans (CT or MRI) with implanted electrodes during the same hospital admission or after explantation (up to 1 month later).

Results

One hundred and thirty-five consecutive patients underwent 140 intracranial electrode implantations. There were 32 children (age < 18, mean 12 years; SD 3.3; range 5–17), all of whom underwent 1.5 T MRI scanning, and 103 adults who underwent 1.5 T MRI and/or 3 T MRI scanning (age > 18 years, mean 35 years; SD 13; range 18–66). The cohort included 74 males (53%). A total of 184 MRI scans were performed with implanted intracranial electrodes including 118 MRI studies at 1.5 T and 66 iEEG-fMRI studies at 3 T (Fig. 1). Five patients underwent intracranial monitoring twice. Follow-up scans were performed up to 1 month after electrode explantation in 68 patients (48%) (Fig. 1). Patient demographics as well as the type and configuration of electrode implantations are summarized in Table 1. The intracranial implantations included 155 depth, 15 subdural, and 14 combined subdural and depth implantations. Specific details of the electrode implantation for each patient are provided in Supplementary Tables 1 and 2.

3 T

Sixty-six adult patients (patients 1–66) underwent iEEG-fMRI at 3 T. Of these, 54 (82%) had limited structural images acquired as part of the iEEG-fMRI protocol (Supplementary Table 1). All patients except two (patients 1 and 35) had MRI ($n = 44$) and/or CT ($n = 20$) scans performed immediately after electrode implantation which was used as the baseline prior to the iEEG-fMRI study. Twenty-six patients (39%) had follow-up MRI ($n = 7$) and/or CT ($n = 22$) scans performed within 1 month of iEEG-fMRI study to assess for any possible complications. There were no clinical adverse events associated with iEEG-fMRI data acquisition in any patient. In addition, no imaging evidence of complications were seen in the 3 T MRI scans or any follow-up scans (1.5 T MRI or CT) apart from those associated with electrode implantation itself (Table 2, Supplementary Table 1).

1.5 T

One hundred and eighteen patients (including 44 who also underwent iEEG-fMRI) had 1.5 MRI scans with implanted

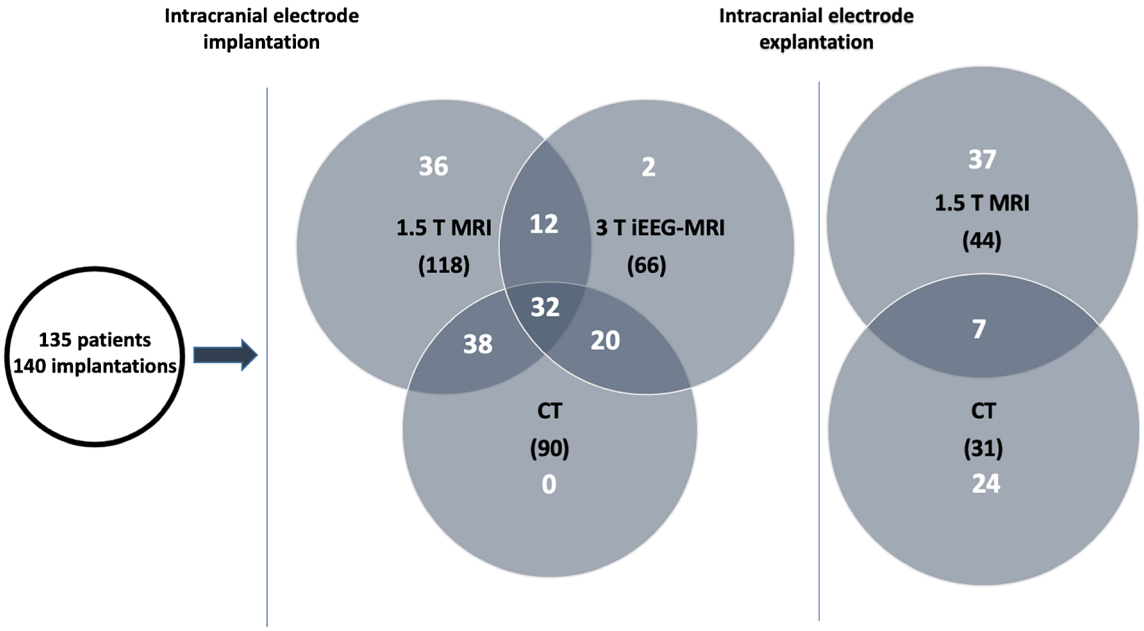

Fig. 1 Summary of post-implantation and post-explantation studies. Numbers in black represent total numbers of the respective scans

Table 1 Patient demographics, electrode types, and electrode configuration

Study	Age (years)		Sex	Electrode type			Number of electrodes			Number of contacts		
	Mean	Range		Depth	Subdural	Depth and subdural	Total	Mean (per patient)	Range (per patient)	Total	Mean (per patient)	Range (per patient)
1.5 T MRI (n = 118)	29.3	5-66	63 m (53%)	107	4	7	1441	12.2 (SD 4)	5–22	5704	86.4 (SD 24.7)	48–146
3 T iEEG-fMRI (n = 66)	35.3	19-65	32 m (48%)	48	11	7	738	11.18 (SD 3.4)	5–20	10,394	88 (SD 25.6)	44–154
Total (n = 184)	29.9	5-66	74 m (53%)	155	15	14	2179	11.86 (SD 3.8)	5–22	16,098	87.5 (SD 25.3)	44–154

electrodes. There were no new adverse events or imaging evidence of complications related to MR scanning at 1.5 T, except those related to electrode implantation (Table 2). Subsequent post-explantation imaging (performed within a month) showed the expected resolution of the existing complications related to electrode implantation (Supplementary Table 2).

Evolution of complications related to implantation

Table 2 summarizes the radiological evidence of complications seen in the present study, all of which were likely related to electrode implantation itself. All patients who had pneumocephalus, extra-axial fluid collections, and focal brain edema related to electrode implantation had resolution on follow-up imaging with no worsening despite undergoing a 3 T iEEG-fMRI study. Two patients (patients 6 and 28) had extra-axial fluid collections at the craniotomy site and two (patients 8 and 41) had focal edema on post-electrode explantation imaging which was not seen in the immediate post-implantation imaging (Supplementary Table 1). These complications are known to occur with electrode implantation and explantation [19, 24]. Patients who developed electrode implantation-related hemorrhage (patients 41, 42, 45, 48, 50, and 95) displayed no worsening of the hemorrhage and showed the expected temporal course of resolution (Supplementary Tables 1 and 2). Post-operative images acquired in 38 patients who underwent epilepsy surgery at the time of electrode explantation showed the expected post-surgical changes only (Supplementary Tables 1 and 2).

Literature review

Our literature search identified 17 studies of which five used phantom models [7, 10, 11, 25, 26], one used a phantom and an animal model [27], one used a combination of phantom and human studies [28] and 10 were human studies [3, 12–14, 29–34] (Table 3). Ten studies used Ad-Tech electrodes. None of the human studies reported complications attributable to MRI scanning. Prior to our study, the largest human study included 86 patients with implanted Ad-Tech electrodes who had MRI scans obtained using a 1.5 T Signa GE Medical Systems scanner [32]. These 86 patients underwent 98 implantations that included 143 depth electrodes, 688 subdural strips, and 38 subdural grid electrodes. Another study included 50 patients that underwent implantation of Ad-Tech branded Spencer platinum and Wyle cylindrical subdural electrodes and were scanned at 1.5 T using a General Electric Signa scanner [33]. No scanning-associated complications were reported. Several studies have reported no complications associated with MRI scanning at lower field strengths in patients implanted with Ad-Tech electrodes [28, 29] and electrodes from other manufacturers [30] (Table 3).

Table 2 Summary of complications identified in post-implantation and post-explantation imaging studies

Complication type	Number	Patient ID	Implantation type	Post-implantation imaging (*n*)			Post-explantation imaging (*n*)		
				CT only	MRI only	CT + MRI	CT only	MRI only	CT + MRI
Pneumocephalus	17	2, 4, 5, 8, 12, 15, 18–20, 28, 41, 43, 46, 47, 68, 107, 119	SD (7) SD + D (2) D (8)	9	3	2	2 (*1)	1	0
Pneumocephalus + extra-axial fluid collection	13	6–10, 13, 16, 20, 21, 28, 30, 47, 50	SD (5) SD + D (5) D (3)	5	2	1	6	1	2 (*2)
Extradural fluid collection including hematoma	14	9, 33, 41, 42, 53, 59, 64, 75, 76, 95, 111, 118, 121, 122	SD (1) SD + D (4) D (8)	0	7	7	1	1	0
Parenchymal hematoma	3	43, 48, 50	D (3)	0	1	2	2	0	0
Small subdural hematoma	1	133	D (1)	0	0	0	0	1	0
Focal edema	2	14, 41	D (2)	0	1	0	1	0	0

Details for each patient are shown in Supplementary Tables 1 and 2

Abbreviations: *D* depth, *SD* subdural

*Post-resection changes

Prior to the present study, our center had the largest safety experience with iEEG electrodes at 3 T and was the only center to report human safety studies at 3 T. Specifically, in three different studies, we reported no complications in 15 patients with implanted Ad-Tech subdural grid, strip, and depth electrodes who underwent iEEG-fMRI at 3 T using a GE Signa LX or GE Discovery MR750 scanner [12–14]. Another study reported no complications associated with 1.5 T or 3 T scanning of eight patients implanted with a total of 271 Ad-Tech electrodes [3].

Discussion

We reviewed the safety of performing 184 MRI scans at 1.5 T or 3 T on 135 patients and identified no adverse events or complications during or after the MRI studies apart from those that are known to occur with intracranial electrode implantation and have been reported previously [19, 24]. To our knowledge, this is the largest study assessing adverse events related to scanning patients with implanted iEEG electrodes.

Our study is unique as it assessed the clinical safety of iEEG electrodes at 3 T in a large group of patients. It is also one among only two studies, to our knowledge, that specifically investigated clinical safety at 1.5 T [32]. Notably, previous human studies identified in our literature search focused on MRI image quality and artifact reduction [3, 28, 30, 31], stereotactic localization methodology [29], safety of MRI-guided stereotactic surgery [33], and iEEG-fMRI analysis [12–14].

Our study is strengthened by the fact that we studied patients at 3 T as well as 1.5 T. Our study is consistently the only other human study that specifically investigated the safety of implanted depth and subdural electrodes at 1.5 T, which did not document any complications [32]. Of the 40 patients who had complications identified in post-implantation or post-explantation scans, two patients (patients 6 and 133) had complications seen only in their post-explantation scans probably related to subdural implantation and electrode explantation. Of the 38 patients that had mild, expected complications identified in MRI or CT scans obtained shortly after electrode implantation, 36 had repeat imaging (30 before explantation and 18 after explanation). The remaining two patients (patients 68 and 75) had very minor complications that were felt not to require any further follow-up imaging. It is reassuring that in these patients, there was no worsening or expansion of these abnormalities which also showed the expected temporal course of resolution. Thus, no adverse events specifically attributable to MRI scanning at 1.5 T and 3 T scanning were identified.

Focal edema after implantation of intracranial electrodes is probably under-reported. A recent meta-analysis showed a 1.3 % and 3.5% overall complication rate for depth and subdural/depth electrodes, respectively, although the specific rates of focal edema were not reported [4]. There are only a few studies that specifically investigated this complication, probably because they are asymptomatic and transient. Asymptomatic local edema was reported in 25% of patients in post-explantation (not post-implantation) MRI scans after subdural strip electrode implantation in a study specifically investigating clinically silent MRI findings [35]. In another study,

Table 3 Previous studies mentioning safety and complications associated with MRI scanning in patients with intracranial EEG electrodes

Study	Center	Study type	Electrode brand	iEEG coverage (human data)	No. of patients studied	MRI magnet strength and manufacturer	Complications (Y/N, human data)
Carmichael et al. [10]	UCL Institute of Neurology, London, UK	Phantom	Ad-Tech, Racine, WI	NA	NA	Siemens 3 T Trio, 1.5 Tavanto, GE 3 T Signa Excite	NA
Bhattacharyya et al. [25]	Cleveland Clinic Foundation, Cleveland, USA	Phantom	Ad-Tech, Racine, WI, and Integra NeuroSciences	NA	NA	1.5 Tesla Espree system (Siemens, Erlangden, Germany) fMRI-paradigm	NA
Zhang et al. [26]	UCLA School of Medicine, Los Angeles, USA	Phantom	Ni–Cr alloy (Superior Tube Company, Norristown, PA)	NA	NA	1.5 T General Electric Signa	NA
Carmichael et al. [9]	UCL, London, UK	Phantom	Ad-Tech, Racine, WI	NA	NA	1.5 T GE Signa, GE 3 T Signa Excite system Siemens 3 T TIM Trio System	NA
Boucousis et al. [7]	University of Calgary, AB, Canada	Phantom	Ad-Tech, Racine, WI	NA	NA	3 T GE Discovery MR750	NA
Ciumas et al. [27]	TIGER, INSERM, France	Phantom, Animal	DIXI, Alcis, Besancon, France	NA	NA	1.5-T Siemens Sonata MRI system fMRI-paradigm	NA
Duckwiler et al. [28]	UCLA Medical Centre, Los Angeles, USA	Phantom, human	Platinum (maker not mentioned)	One electrode each in temporal	1	0.3 T Fonar B-3000 M, Melville, NY	N
Kratimenos et al. [29]	NHN Queen's Square, London, UK	Human	Ad Tech Platinum Spencer	41 electrodes (total)	7	0.5 T	N
Meiners et al. [30]	University Hospital, Utrecht, Netherlands	Human	Brain Electronics, De Bilt, the Netherlands	NA	3	0.5 T	N
Brooks et al. [31]	The Graduate Hospital, Philadelphia, PA, USA	Human	Rhodes Medical Instruments, USA	Mesiotemporal (most common)	30	1.5 T Signa system, GE Medical systems, Milwaukee	N
Davis et al. [32]	Rhode Island Hospital, RI, USA	Human	Ad-Tech, Racine, WI	143 depth electrodes, 688 subdural strips, 38 subdural grids (98 implantations)	95	1.5 T Signa, GE Medical Systems (105 MR scans)	N
Ross et al. [33]	University of Michigan Medical Centre, MI, USA	Human	Ad-Tech Spencer platinum and Wyle cylindrical subdural (Ad-Tech, Racine, WI)	NA	50	1.5 T General Electric Signa	N
Cordova et al. [34]	Medical College of Georgia and VA Medical Center, Augusta, Georgia	Human	NA	NA	1	1.5 T GE Sigma	N
Cunningham et al [13].	University of Calgary, AB, Canada	Human	Ad-Tech, Racine, WI	NA	2	3 T GE Signa LX fMRI-paradigm	N
Yang et al. [3]	New York University Medical Center, NY, USA	Human	Ad-Tech, Racine, WI	271 (electrode arrays)	8	1.5 and 3 T	N
Beers et al. [11]	University of Calgary, AB, Canada	Human	Ad-Tech, Racine, WI	NA	11	3 T GE Signa LX fMRI-paradigm	N
Aghakhani et al. [12]	University of Calgary, AB, Canada	Human	Ad-Tech, Racine, WI	54 (subdural grid, strip, and depth electrodes)	12	3 T GE Signa LX fMRI-paradigm	N

however, edema was reported in 2.5% of patients after subdural electrode implantation and in 1.9% after depth electrode implantation [21]. Similar to the aforementioned studies, we found that 2/140 patients (1.4%, patients 8 and 41) had focal edema, but notably, it was observed only in their post-explantation scans and not in their post-implantation scans.

The major concerns and risks associated with implants in the MRI scanner are due to the possibility of device movement, radiofrequency-induced thermal tissue injury, and inadvertent neuronal stimulation due to switching magnetic fields which can induce current in the electrodes or electrode tails [7]. Ferromagnetic metals are a major concern relating to device movement, and non-ferromagnetic metals such as platinum do not deflect in a magnetic field. Neuronal damage from radiofrequency-induced thermal injury is considered to occur with a prolonged increase of 5 °C above body temperature [36, 37]. Lastly, any induced voltage must not exceed 100 mV at a frequency less than 10 kHz in order to prevent magnetic field induced currents that can cause inadvertent tissue injury [36].

To address these possibilities prior to scanning patients at 3 T, we performed a phantom head model study complying with ASTM guidelines for safety of iEEG-fMRI at 3 T [38]. We showed that our iEEG-fMRI protocol, which included structural imaging sequences as well as 60 min of continuous fMRI, was not associated with significant electrode displacement, temperature increase, or induced currents [7]. However, we observed that high "specific energy absorption rate" (SAR) sequences such as fast spin echo (FSE) and fluid-attenuated inversion recovery (FLAIR) that are not necessary for an iEEG-fMRI study, but not low SAR sequences such as 3D T1-weighted SPGR, were associated with significant heating [7]. Other phantom safety studies have also been performed. For example, Carmichael et al. [10, 11] also demonstrated the safety of intracranial electrodes at 1.5 T and 3 T using a phantom head model provided a head-transmit coil was used, electrode tails were separated, connecting cables were placed along the *Z* axis, and SAR limits were observed. It was also found that structural sequences such FSE generated more electrode heating at 3 T than at 1.5 T [10]. Thus, high SAR sequences such as FSE should be avoided in patients with implanted EEG electrodes. Non-permissible levels of heating have also been reported when electrode tails are shorted and in close proximity [7, 10]. No notable differences have been demonstrated related to heating between depth and grid electrodes and with the number of electrodes [7, 11].

Other studies have assessed the MR safety of intracranial EEG electrodes at lower field strengths. These include phantom studies performed at 0.3 T [28] and 1.5 T [10, 11, 25, 26] using subdural strip, grid and depth electrodes made of materials ranging from stainless steel, nichrome, as well as platinum and its alloys. Another study showed that parasagittal electrode implantations with terminating wires located anterior to a 1.5 T magnet were associated with increased heating compared to coronal electrode implantations with terminating wires located posterior to the magnet [27]. Animal or combined animal/phantom studies have also confirmed the safety of EEG electrodes at 1.5 T [27].

Limitations

One limitation of this study is its retrospective nature. Another limitation is the variability of electrode implantation in the patients. However, this variability is unavoidable as the electrodes were implanted according to clinical need. In addition, mild symptoms which may not have been clinically significant might not have been captured. However, the absence of radiological complications attributable to scanning alone is reassuring and possibly mitigates this limitation. On the other hand, absence of complications at radiological level related to MRI scanning does not necessarily exclude the possibility of thermal injury at tissue level. Furthermore, susceptibility artifact on MR images could mask small lesions immediately adjacent to an electrode. However, such lesions, if present, are likely to be clinically insignificant, consistent with the observations made in the present study. Implanted electrodes by themselves are known to cause tissue injury and microscopic focal lesions [39, 40]. Histopathological examination of depth electrode tracts of patients who underwent MR scanning may shed some light on whether additional damage occurs at the tissue level. In addition, imaging all patients using MRI rather than CT may help better identify post-procedural complications.

Conclusion

Structural MRI scanning at 1.5 T with implanted intracranial electrodes and iEEG-fMRI at 3 T MRI are not associated with any major complications or adverse events using the protocols and electrodes described herein, which avoid high SAR sequences. Thus, while MRI scanner protocols vary across centers, low SAR sequences should be used with implanted intracranial electrodes based on the evidence from phantom studies and our clinical experience. Ideally, manufacturers should ascertain the MRI safety of intracranial electrodes given the increased use of intracranial EEG. In the meantime, reporting of clinical safety and adverse events by clinicians is crucial for monitoring the safety of such devices.

Abbreviations CT, Computed tomography; fMRI, Functional magnetic resonance imaging; FLAIR, Fluid attenuated inversion recovery; FSE, Fast spin echo; iEEG, Intracranial electroencephalography; SAR, Specific energy absorption rate

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00234-021-02661-7.

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Data availability All relevant de-identified data are available on request.

Declarations

Ethics approval and consent to participate All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standard.

Informed consent For this type of study, formal consent is not required.

Consent to participate Not applicable

Consent for publication The authors consent for publication of this work in Neuroradiology.

Conflicts of interest None of the authors has any conflict of interest to disclose.

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