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Electrode placement accuracy in robot-assisted epilepsy surgery: A comparison of different referencing techniques including frame-based CT versus facial laser scan based on CT or MRI

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ABSTRACT

Background: Precise robotic or stereotactic implantation of stereoelectroencephalography (sEEG) electrodes relies on the exact referencing of the planning images in order to match the patient's anatomy to the stereotactic device or robot. We compared the accuracy of sEEG electrode implantation with stereotactic frame versus laser scanning of the face based on computed tomography (CT) or magnetic resonance imaging (MRI) datasets for referencing.

Methods: The accuracy was determined by calculating the Euclidian distance between the planned trajectory and the postoperative position of the sEEG electrode, defining the entry point error (EPE) and the target point error (TPE). The sEEG electrodes (n = 171) were implanted with the robotic surgery assistant (ROSA) in 19 patients. Preoperative trajectory planning was performed on three-dimensional (3D) MRI datasets. Referencing was accomplished either by performing (A) 1.25-mm slice CT with the patient's head fixed in a Leksell stereotactic frame (CT-frame, n = 49), fused with a 3D-T1-weighted, contrast enhanced- and T2-weighted 1.5 Tesla (T) MRI; (B) 1.25 mm CT (CT-laser, n = 60), fused with 3D-3.0-T MRI; (C) 3.0-T MRI T1-based laser scan (3.0-T MRI-laser, n = 56) or (D) in one single patient, because of a pacemaker, 3D-1.5-T MRI T1-based laser scan (1.5-T MRI-laser, n = 6).

Results: In (A) CT-frame referencing, the mean EPE amounted to 0.86 mm and the mean TPE amounted to 2.28 mm (n = 49). In (B) CT-laser referencing, the EPE amounted to 1.85 mm and the TPE to 2.41 mm (n = 60). In (C) 3.0-T MRI-laser referencing, the mean EPE amounted to 3.02 mm and the mean TPE to 3.51 mm (n = 56). In (D) 1.5-T MRI, surprisingly the mean EPE amounted only to 0.97 mm and the TPE to 1.71 mm (n = 6). In 3 cases using CT-laser and 1 case using 3.0 T MRI-laser for referencing, small asymptomatic intracerebral hemorrhages were detected. No further complications were observed.

Conclusion: Robot-guided sEEG electrode implantation using CT-frame referencing and CT-laser-based referencing is most accurate and can serve for high precision placement of electrodes. In contrast, 3.0-T MRI-laser-based referencing is less accurate, but saves radiation. Most trajectories can be reached if alternative routes over less vascularized brain areas are used.

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1. Introduction

Stereotactic electroencephalography (sEEG) is an established technique for invasive presurgical localization of irritative and seizure onset zones, facilitating tailored epilepsy surgery [1]. Previous studies on sEEG electrode implantation describe classical frame-based procedures [2], and recently, also robot-guided frame-based or frameless methods [3]. Robot-assisted sEEG implantation has been described safe and effective concerning the detection of the epileptogenic zone in adults [4] as well as in pediatric patients [5]. There are numerous methods described for robot-assisted implantation, which use different referencing techniques [6,7].

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Precision is crucial in sEEG to place electrodes in the desired area and avoid vessels, which laceration can cause intracerebral hemorrhages, as observed in 1–2% of patients undergoing sEEG [8]. In order to improve accuracy, various methods were added to the preoperative routine. A precise technique is performing a computed tomography (CT) with CT-angiography, having the patient's head fixed in a stereotactic frame [7]. Another approach is to perform a thin layer CT scan of the nonhead-fixed patient and to fuse it with the preoperative magnetic resonance imaging (MRI), in which implantation areas were defined before the surgery. Both methods expose the patient to a large amount of radiation. A radiation-free approach was evaluated recently in a pilot study [4], where all patients were implanted based on an up to five-day-old MRI, which was also used for a surface laser scan of the face. The precision was lower, but seemed sufficient for sEEG electrode implantation, as all target areas were properly reached and no relevant bleedings occurred.

So far, no direct comparison of different referencing methods using the same robotic guidance technique has been published.

Therefore, in this study, patients from two different epilepsy centers were recruited, one center performing the referencing process with a stereotactic frame and the other one performing surface scanning of the face either based on thin layer CTs or three-dimensional (3D) MRIs. The accuracy of the sEEG electrode placement was estimated for all three referencing methods. The Euclidian distance between the preoperatively planned trajectory and the postoperative position of the sEEG electrode was calculated, defining the entry point error (EPE) and the target point error (TPE).

2. Patients and methods

2.1. Patient selection and preoperative planning

All patients evaluated in this study were treated at the epilepsy centers of the University Hospital in Frankfurt am Main and the Schoen Klinik Vogtareuth, both in Germany, between 2012 and 2018. This study is part of a retrospective analysis regarding quality assurance of invasive electroencephalography (EEG) recordings and as such approved by the local ethics committees. The classification of seizure types, epilepsies, and drug resistance was based on the definitions proposed by the International League Against Epilepsy (ILAE) [9–11]. Patients suffered from medical refractory epilepsy for an average of 15 years (range 7–28 years) and underwent a comprehensive presurgical workup including surface video-EEG monitoring [12,13]. The decision for further invasive sEEG diagnostics was made based on these results in an interdisciplinary epilepsy case conference. In all patients who were treated in Frankfurt, the preoperative planning was performed on 3D MRI with T1-weighted plus Gadolinium contrast agent and T2-weighted images, slice thickness of 1 mm (Siemens Magnetom Skyra 3 Tesla, Erlangen Germany). In Vogtareuth, patients were examined with a 3D MRI with T1-weighted plus contrast agent and T2-weighted space images, slice thickness of 0.6 mm (Siemens Magnetom Symphony 1.5 Tesla, Erlangen, Germany). The planning process was performed by at least one board-certified neurologist or neuropediatrician with special training and expertise in epilepsy care together with a board-certified neurosurgeon on the current planning software of the Robotic Surgery Assistant (ROSA, Zimmer Biomet Robotics, formerly MedTech, Montpellier, France).

2.2. Referencing processes

In patients referenced with the stereotactic frame (Leksell Frame, Elekta, Stockholm, Sweden), a 0.5-mm spiral CT scan (Toshiba Aquilion, Canon Medical Systems Corporation, Tochigi, Japan) was performed in general anesthesia (Fig. 1, CT-frame). Referencing was done by connecting the stereotactic frame to the robot and mounting the Leksell-frame registration plates to the frame. Thereafter, the reference points were collected with a pointer probe installed on the robotic arm. The preoperative planning MRI was previously fused using the ROSA planning software. In patients referenced with a thin-layer spiral CT scan (Philips CT Ingenuity, Best, Netherlands) with a slice thickness of 1.25 mm, the head was fixed with a sharp Mayfield clamp (DORO; Pro Med, Freiburg, Germany) and connected to the robot. Thereafter, the referencing process was carried out with a surface laser scan of the face, based on the 3D CT scan face reconstruction (Fig. 2, CT-laser). The last two groups of patients were referenced with the preoperative planning MRI only, as described above. Afterwards the referencing process was carried out with surface laser scanning of the face, based on the surface of the 3D MRI face reconstruction (Fig. 2, 1.5-T or 3.0-T MRI-laser).

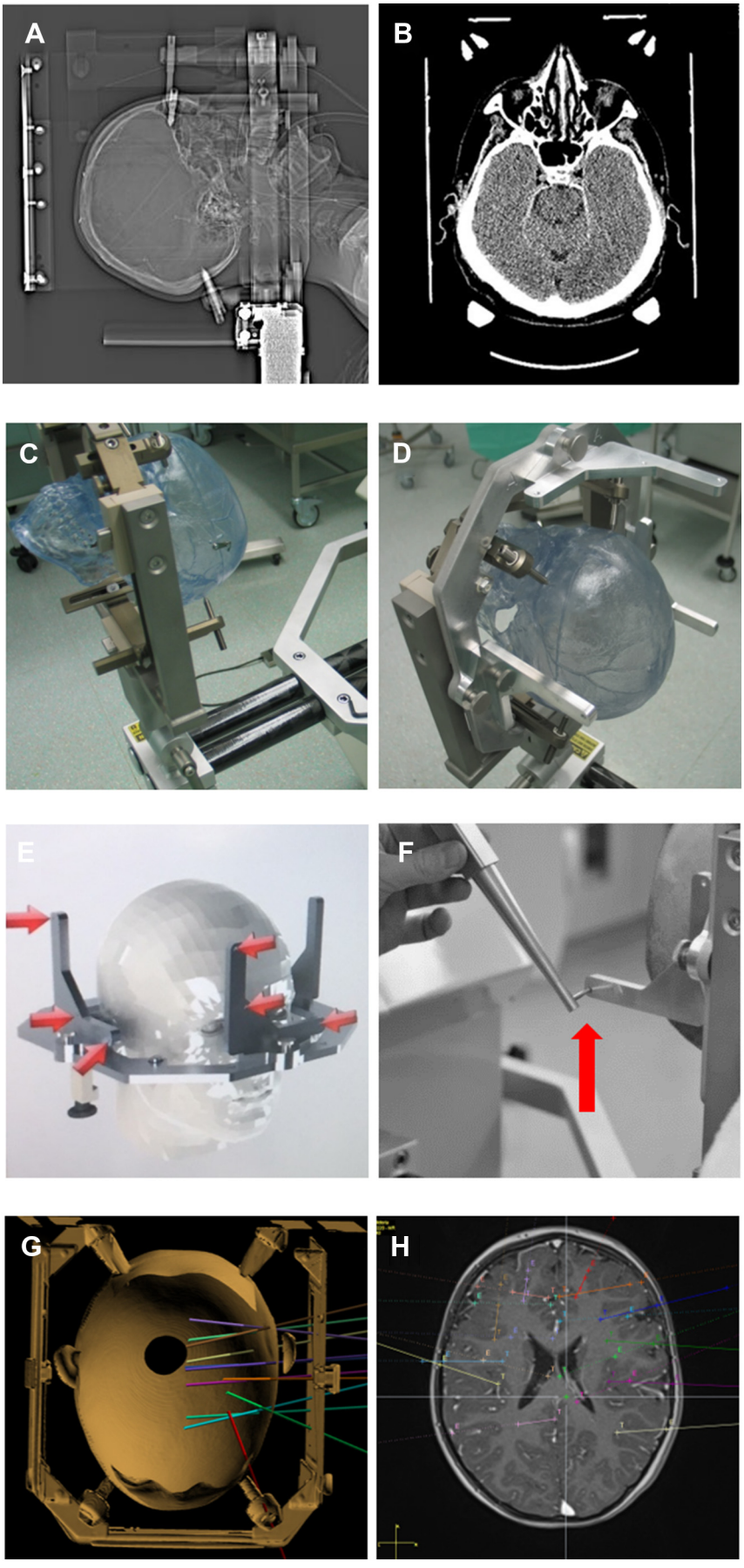
2.3. Robot guided sEEG electrode implantation

All procedures were performed using the same ROSA robot system. Electrode implantation (Spencer Probe Depth Electrodes, 1.1-mm diameter, Ad-Tech Medical, Wisconsin, USA) was performed in a standardized manner as previously described [3,4]. In short, after the referencing process, the electrode entry points were marked with the laser pointer, and in this area, the hair was slightly shaved. This was followed by skin asepsis and sterile drapes. Thereafter, the robot arm drove with the instrument holder to the entry point. A stich incision was made through the instrument holder. The trephination was performed with a motorized 2.1-mm twist drill (Salcman, Elekta, Stockholm, Sweden) according to the previously measured bone thickness. The dura, the arachnoid, and the cortex surface were then perforated using a monopolar coagulation device (Force FX Electrosurgical Generator, Valleylab, Colorado, USA), and an anchor bolt was placed into the burr hole. A blunt stylet (0.85 mm) was used for electrode guidance (Spencer Probe Depth Electrodes, 1.1-mm diameter, Ad-Tech Medical, Wisconsin, USA). Finally, the electrode was fixed with the adjacent screw to the anchor bolt. The average time consumption for planning and implanting the electrodes was estimated for each method, based on the surgeon's report.

2.4. Postoperative imaging and procedure

After implantation, a 1.25-mm CT scan was performed in order to exclude any surgical complication and to confirm the location of the sEEG electrodes. In those patients, who received frame-based referencing, again a 1.5-T MRI was performed and fused with the preoperative planning data to determine the accuracy of positioning. The patients were then brought to video-EEG monitoring for long-term recording. The duration of the invasive video-EEG monitoring depended on the number of recorded seizures and completion of stimulation procedures. Between seven and ten days after implantation, the sEEG recordings, the localization of the irritative zone, seizure onset zone, and putative epileptogenic zone as well as the surgical resectability were discussed at the interdisciplinary case conference. At the end of the invasive video-EEG monitoring, all electrodes were removed, the patient

Fig. 1. Computed tomography (CT) Leksell-frame-based referencing (CT-frame referencing). A) Scout of the thin-layer CT scan with the patient head fixed in a Leksell frame. B) Axial slice section of the thin-layer CT scan from Fig. 1A. C) Demonstration of the fixation of a phantoms head to the Leksell frame and the robot, from both perspectives, D) respectively. E) Registration points (multiple arrows) for the F) robot pointer probe (single arrow) for CT-frame based referencing of the robot; frame registration with G) Three-dimensional (3D) CT reconstruction and H) fusion with 1.5-T magnetic resonance imaging (MRI) planning data.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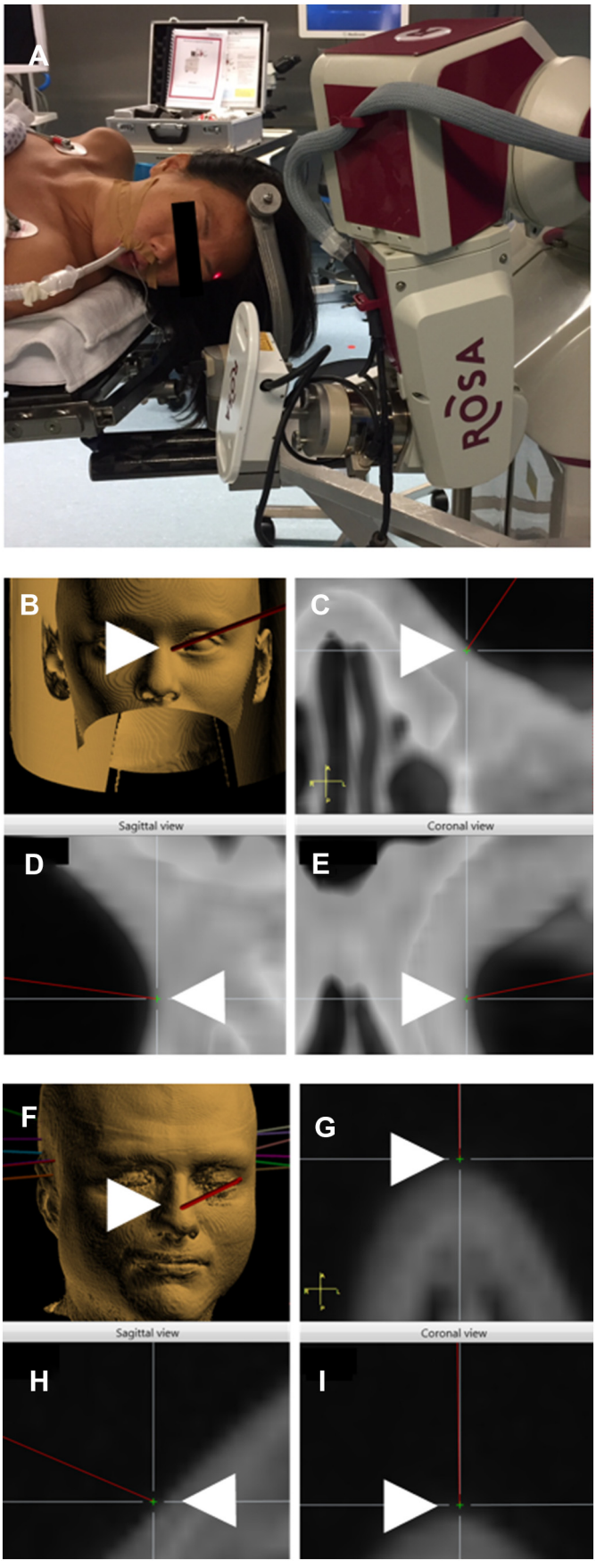
discharged and, if planned for surgery, readmitted between one and three months later.



2.5. Calculation of implantation accuracy

Data entry and analysis was performed using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA). The calculation of the precision was based on the preoperative 3D trajectory, planned on a 1.0-mm 3.0-T MRI (CT-laser group and 3.0-T MRI-laser group) or 0.6-mm 1.5-T MRI (CT-frame group and one patient in the MRI-laser group) and the postoperative 3D reconstruction of the electrodes' position on the 1.25-mm CT (both 1.5-T and 3.0-T MRI-laser and CT-laser groups) or 0.6-mm 1.5-T MRI scan (CT-frame group). Preoperative and postoperative data were fused using the ROSA robot software; the planned and the actual positions of the electrodes were determined. The planned entry point was defined as the point where the planned trajectory enters the surface of the calotte; the actual entry point was the center of the electrode on the calotte surface. The planned target point was defined as the intracerebral end of the trajectory, the actual target point as the last contact of the electrode, respectively. The accuracy was then calculated applying the Euclidian distance as described by Kelman and collaborators [14] for the tip of the electrode (target point error, TPE) and the entry point on the scull bone surface (entry point error, EPE). Statistics were performed using Microsoft Excel. Normal distribution of the data in the CT-frame, CT-laser, and the two MRI-laser groups was determined and a *t*-test applied.

3. Results

3.1. Patient data

In total, 19 patients with 171 sEEG electrodes were identified (Table 1). (A) Four patients with 49 sEEG electrodes received CT-frame for referencing, (B) seven patients with 60 sEEG electrodes received CT-laser, which surface was used for referencing with a laser scan of the face and (C) seven patients with 56 sEEG-electrodes received a preoperative planning 3.0-T MRI, using the T1 image surface for referencing. (D) One patient received, due to a heart pacemaker, a preoperative planning 1.5-T MRI; the T1 image surface was used for referencing. All patients had a long history of focal epilepsy, refractory to an average of more than 6 different antiepileptic drugs (AEDs). Planning was performed interdisciplinarily, taking 60–120 min per patient with an average time of 75 min. The average planning time per electrode amounted to 10–15 min. Pathomorphological abnormalities in the preoperative MRI scan were found in all patients. In none of the patients, the implantation of additional subdural stripe or grid electrodes was indicated.

3.2. Localization of the sEEG electrodes

In the CT-frame group, all implantations were designed multilobar; in total, 20 frontal electrodes, 12 temporal, 8 parietal, 8 insular, and 1 occipital electrode were implanted. In the CT-laser referencing group, 23 electrodes were implanted temporal, 32 frontal, 4 parietal, and 1 insular. In the 3.0-T MRI-laser referencing group, 42 electrodes were implanted

Fig. 2. Referencing with CT and MRI datasets and laser scan of the patients' surface (CT-laser, 3.0- T MRI-laser referencing). A) Surface matching. The laser scanner is fixed to the robot; the laser beam is seen as a small red spot on the patients face. B) Position of the laser beam during surface registration on 3D reconstruction of the thin-layer CT scan (CT-laser referencing), C) laser beam on axial-, D) sagittal-, and E) coronal-CT slices, respectively. F) Position of the laser beam during surface registration on 3D reconstruction of MRI (3.0- T MRI-laser referencing), G) laser beam on axial-, H) sagittal-, and I) coronal-MRI slices, respectively. It is visible, that the MRI 3D reconstructions and slices are not as even as the CT scans.

Table 1
Demographic and clinical characteristics of patients; number of patients per method (n); Sex (m = male; f = female); Mean age at sEEG (age) in years (yrs) with range; Image modality used for preoperative planning (Planning), the referencing process (Referencing) and postoperative documentation of electrode positioning (Post-Impl.); Implantation site: multilobar (M), temporal (T), or extratemporal (E); Total number of electrodes (n), mean number of electrodes per patient (mean) with range (range); Time between planning MRI and sEEG implantation (Time MRI/Implant) in days with range. * In one patient in the CT-frame group, the planning MRI was one year old and was not included in the calculation.

Method (n)		Sex		Age (yrs)		Image modality			Implant. site			Electrodes			Time MRI/Implant. (days)
		m	f	mean	range	Planning	Referencing	Post-Impl.	M	T	E	n	mean	range	
A	CT-frame (4)	2	2	13	(8–20)	1.5-T MRI	CT	1.5-T MRI	4	–	–	49	12	(10–14)	5 (3–7) *
B	CT-laser (7)	3	4	32	(21–43)	3.0-T MRI	CT	CT	2	2	3	60	9	(5–11)	4 (3–5)
C	3.0-T MRI-laser (7)	4	3	34	(27–46)	3.0-T MRI	3.0-T MRI	CT	4	3	–	56	8	(6–10)	2.5 (1–5)
D	1.5-T MRI-laser (1)	–	1	24		1.5-T MRI	1.5-T MRI	CT	1	–	–	6			3

temporal, 8 frontal, and 6 insular. In the 1.5-T MRI-laser patient, we implanted 3 temporal and 3 occipital electrodes.

3.3. Image quality

The 3D reconstruction of CT and MRI showed that the MRI T1 surface (Fig. 3A) is not as even as the CT surface (Fig. 3B). Furthermore, the air–skin contrast on the plane MRI images appeared less accurate than the air–skin contrast of the CT. Arachnoid surface vessels, as well as sulcal vessels or small white matter vessels were well-recognized on the preoperative T1-weighted images with contrast agent. There was no additional vascular imaging performed, neither with digital subtraction angiography nor with CT angiography.

3.4. Application accuracy

In (A) CT-frame-based referencing, the mean EPE amounted to 0.86 mm (Table 2, 95% confidence intervals [$CI_{95\%}$] 0.71 mm–0.99 mm), the TPE to 2.28 mm ($CI_{95\%}$ 1.91 mm–2.65 mm). Target point accuracy of (B) CT-laser referencing was comparable to CT-frame referencing (Fig. 4, $p = 0.61$, not significant, n.s.) and resulted in a mean TPE of 2.41 mm ($CI_{95\%}$ 2.07 mm–2.75 mm). Regarding the entry point accuracy, CT-laser was significantly less precise compared with CT-frame ($p < 0.001$) with a mean EPE of 1.85 mm ($CI_{95\%}$ 1.64 mm–2.07 mm). Using the (C) 3.0-T MRI-laser referencing, the mean EPE amounted to 3.02 mm ($CI_{95\%}$ 2.67 mm–3.37 mm), the mean TPE to 3.51 mm ($CI_{95\%}$ 3.12 mm–3.89 mm); CT-based referencing, whether with Leksell frame or a laser scan of the face, was significantly more accurate than 3.0-T MRI-based referencing ($p < 0.001$). In the single patient with the pacemaker, (D) 1.5-T MRI-laser was used; surprisingly, the mean EPE amounted only to 0.97 mm ($CI_{95\%}$ 0.41 mm–1.53 mm), the TPE to 1.71 mm ($CI_{95\%}$ 1.19 mm–2.24 mm). For all four methods, the calculated EPE and TPE were correlated with the total intracerebral length of the electrode. Overall, there was no significant correlation between the length of the implanted electrode and the EPE or the TPE; however, we observed more outliers in the 3.0-T MRI-based referencing group (Fig. 5).

Detailed analysis of insular electrodes, in three patients with 3.0-T MRI-laser referencing (two electrodes each), showed an EPE of 3.36 mm and a TPE of 4.07 mm. Three patients with CT-frame referencing received a total of eight insular electrodes with a mean EPE of 0.88 mm (range 0.55 mm–1.24 mm) and a mean TPE of 1.99 mm (range 0.95 mm–4.23 mm). There were no insular implantations using CT-laser referencing. The accuracy of the more oblique temporopolar electrodes was calculated with a mean EPE of 3.38 mm (range 1.35 mm–5.17 mm) and a mean TPE of 3.69 mm (range 1.84 mm–6.18 mm) in patients with CT-laser referencing. In patients who had a 3.0-T MRI for referencing, a mean EPE of 3.99 mm (range 1.75 mm–6.66 mm) and a mean TPE of 4.18 mm (range 1.17 mm–7.51 mm) were calculated. These oblique electrodes were exceptionally long and not representative for a standard implantation scheme; therefore, they were not included in the overall analysis of accuracy, but in the correlation analysis of TPE and electrode's length.

3.5. Complications

No major complications and no new neurological deficits were observed after sEEG electrode implantation or explantation procedures. After implantation, all patients in the CT-laser and the 3.0-T and 1.5-T MRI-laser groups received a CT scan to verify the accuracy of electrode positioning; patients in the CT-frame group received a 1.5-T MRI. No hemorrhages were detected. Because of the fact that patients in the CT-laser and the 3.0-T and 1.5-T MRI-laser groups were part of an audit [3], evaluating implantation and explantation related complications, those patients received a CT scan after sEEG electrode explantation. Four clinically silent intracerebral hemorrhages with a mean volume of 2.3 ml were identified around electrodes in four different patients; three of them were found in patients who had CT-based laser scan for referencing; one had 3.0-T MRI-based referencing. We detected a clinically unapparent subarachnoid hemorrhage (SAH) in one patient; further examination revealed a previously unknown factor VII deficiency. No subdural hematomas were detected. In two patients, broken guidance screws were observed. The first of those patients had a generalized tonic–clonic seizure during monitoring that caused two screws in the right parietal region to break. In the second patient, one occipital guidance screw broke during the monitoring phase, probably because of the patient's sleeping habits on the back. No superficial infection or meningitis was detected; postoperative fever did not occur. Patients were treated for the first three days with ibuprofen or paracetamol. Most patients experienced discomfort during monitoring. In one patient, the electrodes were removed already on the fifth postoperative day as the patient had underestimated the discomfort and did not tolerate the invasive video monitoring. Despite the short duration of monitoring, we recorded a sufficient number of seizures in this patient to determine the epileptogenic zone in the right temporal pole, and surgical treatment was recommended.

4. Discussion

In summary, this analysis shows that CT-frame referencing is the most precise method for determining entry points with an EPE below 1 mm, followed by CT-laser referencing with an EPE below 2 mm, and finally, by MRI-laser referencing with an EPE of about 3 mm (Table 2, Fig. 4). The EPE is most likely influenced by the implantation technique, the referencing process or other external factors. The TPE in addition depends on the space deviation of the electrode material and is most likely influenced by the electrode length; although, we could not show a significant correlation between the TPE and the electrode length. Therefore, the effective position of the electrode, defined by the TPE, was usually higher than the EPE. The TPE in CT-frame referencing amounted to 2.3 mm, followed by CT-laser with 2.4 mm, and by 3.0-T MRI-laser with 3.5 mm. In conclusion, the additional deviation of the electrode diminishes the higher precision of CT-frame referencing compared with that of CT-laser referencing. The 3.0-T MRI-laser referencing method shows the highest TPE of all methods, which is about 1 mm higher; however, it spares radiation exposure for the patient.

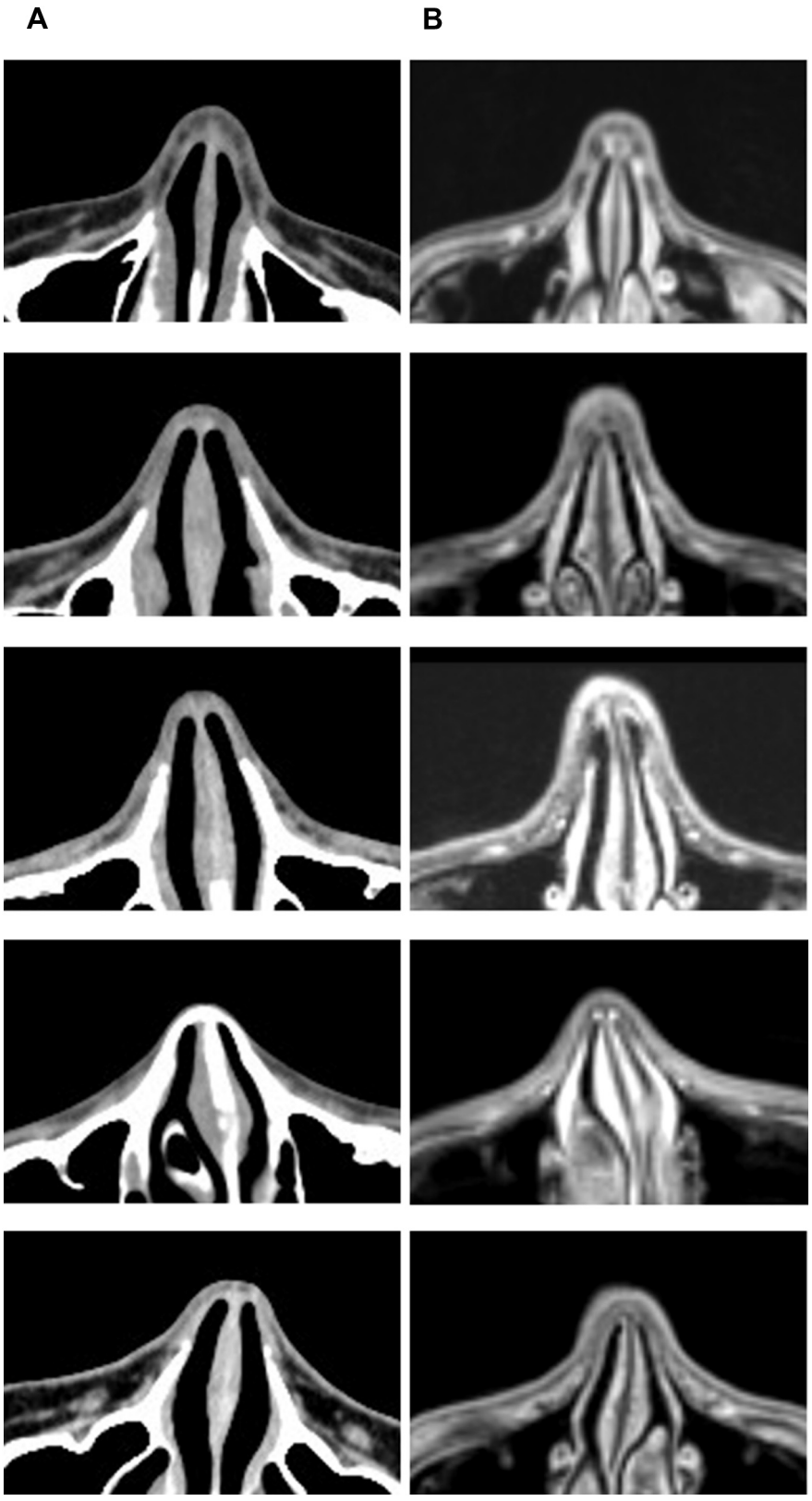


Fig. 3. Comparison of surface contrast in CT versus 3.0- T MRI in five patients. A) Thin layer CT scan for laser scan based surface registration. B) 3.0- T planning MRI scan, the surface of the MRI scan is less even, compared to the CT surface.

4.1. Efficacy of the referencing processes

Compared to the classic frame-based stereotactic implantation method, Abel and collaborators [5] reported a shorter operating time in robot-assisted frameless implantation. Both centers involved in the present study have a similar experience with stereotactic and robot-assisted surgery. Previously, a single Leksell-frame-implanted sEEG electrode lasted between 20 and 30 min, whereas a single ROSA-implanted sEEG

Table 2
Accuracy of robot guided electrode positioning in different referencing methods (method) with number of electrodes per method (n), mean entry point error (EPE), mean target point error (TPE) in mm with standard deviation (SD), 95% confidence intervals (CI_{95}), and range.

Method (n)	EPE mean (SD; $CI_{95\%}$; range) [mm]	TPE mean (SD; $CI_{95\%}$; range) [mm]
A CT-frame (49)	0.86 (±0.51; 0.71–0.99) (0.33–2.64)	2.28 (±1.33; 1.91–2.65) (0.5–4.19)
B CT-laser (60)	1.85 (±0.84; 1.64–2.07) (0.51–3.9)	2.41 (±1.34; 2.07–2.75) (0.76–4.51)
C 3.0-T MRI-laser (56)	3.02 (±1.35; 2.67–3.37) (0.48–6.48)	3.51 (±1.48; 3.12–3.89) (1.04–6.62)
D 1.5-T MRI-laser (6)	0.97 (±0.70; 0.41–1.53) (0.31–2.32)	1.71 (±0.65; 1.19–2.24) (1.22–2.79)

electrode lasted between 5 and 10 min. Thus, resulting to a length of surgery of about 6 to 8 h for ten Leksell-frame-implanted sEEG electrodes, compared with 2 to 3 h for the ROSA, including preoperative imaging or laser scanning, respectively. Since the CT-frame referencing had a lower EPE but a similar TPE as the CT-laser, both methods can be judged almost equally precise regarding the electrode placement (Fig. 4). The 3.0-T MRI-laser is saving one thin-layer CT scan, but had the highest TPE of about 3.5 mm. For complex target areas like the insular cortex, because of its proximity to the branches of the midcerebral artery, trajectory planning and electrode implantation require high precision [15]. Working with the less accurate 3.0-T MRI-laser referencing method requires a large safety zone around each planned electrode. In these patients, we have approached the insula from the parasagittal, where fewer vessels surrounded the trajectory [2] (Fig. 6). Careful planning and large safety zones might minimize complications like bleedings, but inaccurate electrode positioning might still diminish the diagnostic value of EEG recordings. The area of interest for the localization of the irritative and the seizure onset zone might be narrow, a deviation of 3.5 mm could therefore result in a rather unfortunate electrode positioning missing the cortex, and recordings might remain inconclusive. It rests with the surgeon to decide on whether careful planning can outweigh the risk of complications or an insufficient electrode placement.

4.2. Limitations

A limitation of this study is that different referencing processes and different postoperative imaging techniques were carried out at the two different centers. All CT-frame registrations were performed in Vogtareuth, whereas all CT-laser and MRI-laser registrations were performed in Frankfurt. Confounding factors as the team's experience could not have been evaluated. The trajectory planning for the patients in Vogtareuth was based on 1.5-T MRIs, whereas in Frankfurt trajectory planning was performed on 3.0-T MRIs, except for the one patient with the pacemaker. Furthermore, CT-frame slice thickness was smaller and carried out on different CT scanners than the CT-laser registration. Also, the age spectrum of the patients was different between the two centers, in Vogtareuth patients were children or adolescents, in Frankfurt the patients were adolescents and adults. The difference in age also influenced the postoperative control imaging, in Vogtareuth 1.5-T MRIs were performed, whereas in Frankfurt all patients were controlled with thin-layer CTs. The vector error was hence calculated based on the fusion of a preoperative MRI and a postoperative CT or MRI. The fusion of two MRI datasets might differ in accuracy from the fusion of MRI data with a CT scan. This might have an impact on the accuracy of the coordinates we determined, which possibly makes the vector errors we calculated less comparable.

4.3. Radiation exposure

The most serious complication of sEEG electrode implantation is intracerebral hemorrhage. Systematic reviews show epidural (EDH), subdural (SDH), subarachnoid, and intracerebral (ICH) hemorrhages as complications of sEEG electrode implantation [3,16]. Performing catheter-based or CT angiography in advance can help recognize even very small vessels and minimize reasons for hemorrhagic complications. As the results of this study suggest, a 3D CT scan can improve accuracy and therefore also diminish the risk for intracerebral hemorrhages. Particularly in children, radiation exposure should be considered carefully, since several studies have demonstrated that the long-term risk for neoplasia is increasing with the number of CTs performed in childhood [17,18]. The results of this study might justify an additional CT scan for referencing, but hemorrhages can also be avoided by taking some different risk factors during the steps of the sEEG electrode implantation into account. Possible reasons for EDH are bleeding of the diploe veins of the skull during the drilling procedure or blunt dissection of the dura mater and creating an artificial epidural space because of failed dura penetration; EDH can be avoided by fast implantation of the anchor bold in diploe bleedings and a save penetration of the dura mater by drilling 1–2 mm deeper than the thickness of the bone, since the dura is semi tight

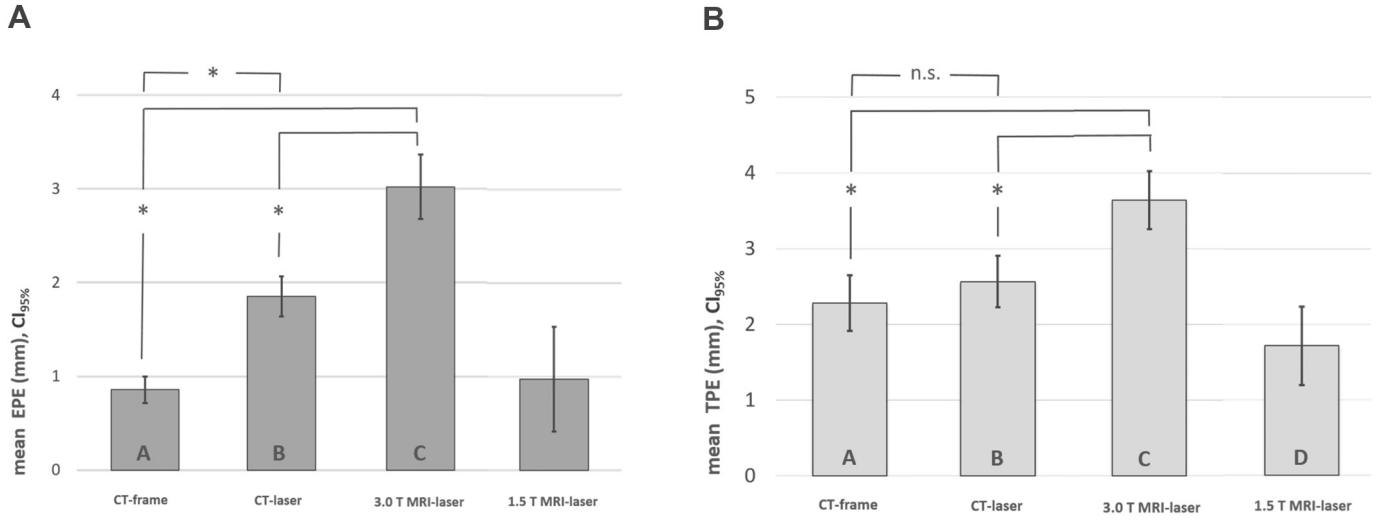


Fig. 4. Accuracy of electrode positioning. A) Mean entry point error (EPE) drawn as the ordinate in the height of the columns (mm) for CT-frame, CT-laser, MRI-laser for 3.0 Tesla (T) and 1.5 T, respectively. B) Mean target point error (TPE) drawn as the ordinate in the height of the columns (mm) which represent the abscissa: CT-frame, CT-laser, MRI-laser for 3.0 and 1.5 T, respectively. For both graphs' error bars are shown as 95% confidence intervals (CI_{95}); highly significant differences ($p < 0.001$) are marked with *, not significant results ($p > 0.05$) with n.s.

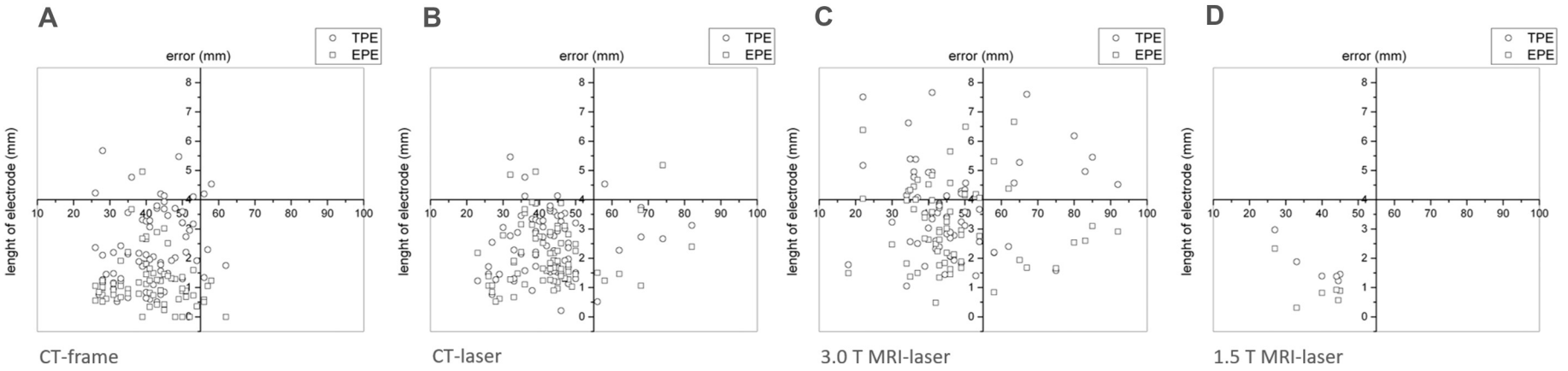


Fig. 5. Correlation between total intracranial length of each electrode with the calculated EPE (squares) and TPE (dots) for the different referencing methods, n.s.; A: CT-frame, B: CT-laser, C: 3.0-T MRI-laser, D: 1.5-T MRI-laser. There was no significant correlation between the total intracranial length of the electrode and the accuracy of implantation. The lower left square depicts electrodes with a length of up to 55 mm and a TPE of less than 4 mm. In the 3.0- T MRI-laser group, more electrodes with a length exceeding 55 mm were implanted. Both low and high TPEs were observed in this subgroup.

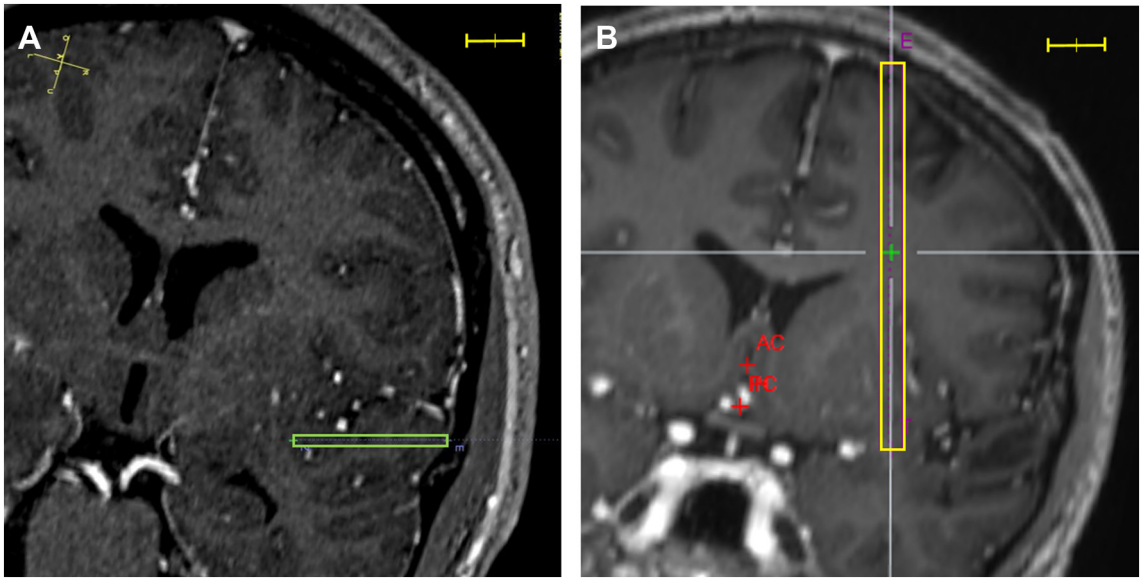


Fig. 6. Strategies in planning of insular electrodes considering the different levels of precision. A) Referencing with the stereotactic frame (CT-frame) with a mean electrode deviation of < 2.5 mm allows a narrow trajectory though the frontotemporal (Sylvian) fissure containing the vessels of the mid cerebral artery. There is a safety zone of 2 mm around the trajectory, drawn in green. B) Alternative to A, a transcortical trajectory with wide safety zone was chosen in a radiation-free approach referencing with 3.0- T MRI and surface laser scan (3.0- T MRI-laser), considering a wider safety zone because of a mean electrode deviation of <3.5 mm. The safety zone (yellow lines) around the trajectory amounts therefore up to 4 mm. Scale bar 10 mm.

fixed to the inner side of the internal tabula of the skull, followed by monopolar coagulation and perforation of the dura. If doing so, attention has to be payed not to injure cortical vessels, which would cause SDH. Therefore, cortical vessels have to be in safe distance of the entry point by taking the estimated EPE into consideration. When crossing the subarachnoid space, the cisterns or sulci should be avoided by entering the cerebrum through gyri, since the sulci often contain small vessels, which might not be seen on MRI or CT, but can cause SAH. In addition, ventricular spaces should be spared, since the ependyma is well-vascularized. However, particularly in hippocampal sEEG electrodes, it is barely avoidable to cross the temporal horn of the ventricle. Finally, particular attention has to be payed to deep white matter veins or arteries; most of them are visible on T1-weighted contrast-enhanced MRIs [19].

The temporal lobe is prone to cause epilepsy, and together with the adjacent insular cortex, it is often targeted for sEEG electrode implantation. Unfortunately, because of the location of the midcerebral artery in the frontotemporal fissure, planning and finding a vessel-free trajectory for insular implantation can be challenging. Alternative trajectories entering the frontal lobe and reaching the insular cortex from a cranial entry point can be planned through less vessel dense brain areas, but they usually require longer electrodes. Depending on the TPE of the different referencing techniques, larger safety areas and vessel exclusion zones should be established. In some temporal implantations, oblique electrode trajectories targeting the temporobasal cortex show a higher TPE, regardless of the referencing technique used for implantation. These implantations turned out to be more complex because of the heavy angulation, and therefore, a larger safety area and vessel exclusion zone should be taken into consideration.

5. Conclusion

Robot-guided sEEG electrode implantation with CT-frame or laser-based referencing is very accurate and can serve for high precision placement of electrodes. In contrast, referencing with 3.0-T MRI only results in a higher vector error. Knowing the advantages and disadvantages of each method provides the surgeon with the opportunity to choose the adequate technique adjusted to the requirements regarding accuracy and radiation exposure.

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