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Surgical outcomes related to invasive EEG monitoring with subdural grids or depth electrodes in adults: A systematic review and meta-analysis

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ABSTRACT

Purpose: Resective epilepsy surgery based on an invasive EEG-monitors performed with subdural grids (SDG) or depth electrodes (stereo-electroencephalography, SEEG) is considered to be the best option towards achieving seizure-free state in drug-resistant epilepsy. The authors present a meta-analysis, due to the lack of such a study focusing on surgical outcomes originating from SDG- or SEEG-monitors.
Method: English-language studies published until May 2018, highlighting surgical outcomes were reviewed. Outcome measures including total number of SDG- or SEEG-monitors and resective surgeries; consecutively followed surgical cases; surgical outcomes classified by Engel in overall, temporal/extratemporal and lesional/nonlesional subgroups were analyzed.
Results: 19 articles containing 1025 SDG-interventions and 16 publications comprising 974 SEEG-monitors were researched. The rate of resective surgery deriving from SDG-monitoring hovered at 88.8% (95%CI:83.3–92.6%) (I^2 = 77.0%;p < 0.001); in SEEG-group, 79.0% (95%CI:70.4–85.7%) (I^2 = 72.5%;p < 0.001) was measured. After SDG-interventions, percentage of post-resective follow-up escalated to 96.0% (95%CI:92.0–98.1%) (I^2 = 49.1%;p = 0.010), and in SEEG-group, it reached 94.9% (95%CI:89.3–97.6%) (I^2 = 80.2%;p < 0.001). In SDG-group, ratio of seizure-free outcomes reached 55.9% (95%CI:50.9–60.8%) (I^2 = 54.47%;p = 0.002). Using SEEG-monitor, seizure-freedom occurred in 64.7% (95%CI:59.2–69.8%) (I^2 = 11.9%;p = 0.32). Assessing lesional cases, likelihood of Engel I outcome was found in 57.3% (95%CI:48.7%–65.6%) (I^2 = 69.9%;p < 0.001), using SDG; while in SEEG-group, it was 71.6% (95%CI:61.6%–79.9%) (I^2 = 24.5%;p = 0.225). In temporal subgroup, ratio of seizure-freedom was found to be 56.7% (95%CI:51.5%–61.9%) (I^2 = 3.2%;p = 0.412) in SDG-group; whereas, SEEG-group reached 73.9% (95%CI:64.4%–81.6%); (I^2 = 0.00%;p = 0.45). Significant differences between seizure-free outcomes were found in overall (p = 0.02), lesional (p = 0.031), and also, temporal (p = 0.002) comparisons.
Conclusions: SEEG-interventions were associated, at least, non-inferiorly, with seizure-freedom compared with SDG-monitors in temporal, lesional and overall subgroups.

1. Introduction

Epilepsy is one of the most prevalent neurological diseases highlighting an incidence of 0.4–1 ‰ and prevalence of 0.4–1 % [1–3]. Approximately 30% of the patients are resistant to antiepileptic drugs [4–7], in which surgical resection constitutes the best therapeutic

option towards achieving the seizure-free status [8]. While noninvasive video-EEG monitor and cranial MRI can be conclusive regarding resective surgery throughout a larger proportion of patients (˜60%), invasive exploration with intracranial electrodes plays a pivotal role for the remaining cases [9–14], often including non-lesional drug-resistant epilepsy, temporal or extratemporal lesional epilepsy with discordant electro-clinical results [8]. To date, two gold-standard methods exist in support of intracranial EEG monitoring (iEEG): the placement of subdural grid electrodes (SDG) and the stereotactic implantation of depth electrodes (stereo-electroencephalography, SEEG) [8,15–19].

SDG and SEEG are opposing, different techniques with their own criteria, philosophy, dissimilar advantages and disadvantages [8].

SDG can (1) envelope the cortical areas upon the surface covering one-third of the cerebral cortex; (2) eloquent areas could more easily be evaluated through the use of SDG than SEEG; and finally, (3) SDG is far less expensive than SEEG [8,16,20].

SEEG may also feature unique advantages: 1) SEEG can record electrical activities from hidden brain structures such as the insula and limbic structures (e.g., amygdala, hippocampus) and sulcal cortical regions, which constitute the remaining **two-thirds** of the cerebral cortex; 2) SEEG can monitor multiple locations within both cerebral hemispheres, allowing us to interpret each epileptic case as a network; (3) the insertion of SEEG electrode does not require craniotomy, and the removal of SEEG electrodes is simple and does not require surgery; (4) radio-frequency thermocoagulation can be performed; (5) resective surgery can be separated by any length of time (often several months) after SEEG, which greatly contrasts with SDG, where resective surgery must be performed immediately following the end of monitoring; and lastly, (6) SEEG is far less dangerous as compared to SDG [8,21–26].

However, SEEG is still less widely used than SDG, due to three main concerns. The first being the logistical constraints (device and methodology), which may seem more complicated in comparison to SDG, which can be placed directly upon the cortex following craniotomy. The second issue refers to its seemingly more invasive nature involving the intraparenchymal placement of needle electrodes versus the use of subdural electrodes. Lastly, the low spatial sampling related to the limited number of implanted contacts per brain structure [8].

Following iEEG exploration, 67% to 96% of patients suffering from intractable epilepsy will undergo resective surgery, [21,22] and eventually become seizure-free, based on a relatively wide interval (34 to 66%) [23,27–29]. This marked deviation within surgical outcomes may be due to the different methodological approaches (SDG – positioned upon the cortical surface; SEEG - placed intraparenchymally), and altering experiences in each of the centers [8,28].

In the current study we aimed to conduct a systematic survey regarding surgical outcomes originating clearly from either SDG or SEEG. To the best of our knowledge, to date, no meta-analyses exploring efficacy of SDG or SEEG have been performed. From another perspective, numerous works have recently been published (between 2016–2017), thus we performed a meta-analysis to elucidate and synthesize the differential surgical outcomes using these two different techniques. It is worth noting that we did not study the complications of iEEG explorations, as meta-analyses concerning complications of SDG and SEEG have only been published recently [24,30].

2. Material and methods

2.1. Literature search and selection of studies

The search for suitable literature and study design was accomplished using guidelines resulting in selecting the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) recommendations [31]. A literature search was performed utilizing Pubmed and EMBASE databases. Pubmed was the primary database accessed. EMBASE was used to find additional literature and to ensure no relevant studies were missed. To assess peer-reviewed articles

containing outcomes of epilepsy surgeries following SDG monitoring, we used these query guidelines: epilepsy AND (SDG OR (Subdural AND grid) OR (subdural AND grids) OR (subdural AND strip) OR (Subdural AND EEG) OR (subdural AND strips)) AND (outcome OR outcomes), leading to 292 Pubmed and 465 EMBASE results (Appendix: Supplemental Digital Content 1).

Following SEEG monitor, surgical outcomes were reached using this method: epilepsy[All Fields] AND (stereotaxic AND (electroencephalography OR EEG)) OR (stereo AND (electroencephalography OR EEG)) OR SEEG AND (outcome OR outcomes), with 221 Pubmed and 360 EMBASE results (Appendix: Supplemental Digital Content 2).

In total, 513 (Pubmed) titles and abstracts were examined for the following inclusion criteria: reported primary outcomes of resective epilepsy surgery and also their follow-up deriving from iEEG monitor, published up through the 20th of May, 2018, and available in English.

2.2. Study selection, data extraction, and assessment of bias

Initial screening was performed by one author (MT). Duplicates were discarded and remaining articles were screened by title and abstract. Full texts were then reviewed by 3 authors (KSzP, DK and CsGy) for inclusion criteria.

After selecting the studies to be included, data were extracted by 2 independent reviewers (MT and CsGy) into separate Microsoft Excel spreadsheets and confirmed for accuracy (Microsoft Excel 2016; Microsoft Corp, Redmond, Washington). The following data were obtained: study design (author, year, number of centers), study population (age, gender ratio, number of patients undergoing invasive monitoring, number of resective surgeries and followed cases), Engel classification at the last postoperative visit, temporal-extratemporal subgroups, MRI positive-MRI negative subgroups.

We assessed the risk of bias in the primary studies utilized for our systemic review through the bias domains based on the guidelines of the Cochrane Collaboration's tool for assessing risk of bias [32]. The domains that were relevant to our analysis were reporting bias (selective reporting) and attrition bias (incomplete outcome data). Assessment of publication bias was conducted with Funnel plots created using Comprehensive Meta-Analysis (CMA) Version 3.0 Software (Biostat, Englewood, New Jersey).

2.3. Outcome measures

Thirty-one articles met eligibility criteria and were examined thoroughly for the following exclusion criteria: postoperative follow-up duration < 6 months; overlapping patient series; studies containing solely children; and finally, insufficiently disaggregated outcomes reported. Individual patients were disqualified from analysis if they received both subdural and depth electrode implantation. All patients were screened with regards to whether they opted for resective surgery, and, subsequently, the follow-up was also assessed. To evaluate efficacy, followed resective cases were pooled and labeled as Engel I or Engel II-IV surgery outcomes, regarding the Engel classification system [33].

2.4. Statistical analysis

The pooled event rate was calculated in the occurrence of specific events. A random effect model was applied in all cases of analyses using the DerSimonian and Laird approach. Statistical heterogeneity was analyzed using the I^2 and the Chi-Square test to gain probability-values; $p < 0.1$ was defined to indicate significant heterogeneity.

Subgroups of SDG and SEEG methods were created in the analysis of surgery outcomes. Statistical analyses were performed using CMA. Forest plots display the result of the meta-analysis. Meta-regression analyses were used for investigating the effect of the follow-up. To check and prevent publication bias, Funnel plots and Eggers' tests were

carried out with no effect on the final results in all situations (total number of resections, followed resections, and in overall, temporal-extratemporal, lesional-non-lesional subgroups) performed (Appendix: Supplemental Digital Content 8–14).

3. Results

A total of 31 studies were identified, representing a period from 1996 [34] through 2017 (Appendix: Supplemental Digital Content 1 and 2) [28,35–39]. All were single-institution studies [18,23,27–29,36–38,40–58], except for four cases, which reported data from two [34,39,59] or eleven [35] centers, respectively. In total, four articles [28,37,39,40] reported both SDG and SEEG interventions; and surgery outcomes could be clearly differentiated throughout these cases.

4. Demography

These studies included a total of 1025 SDG interventions (median: 49, range: 2–177) in 19 articles [28,29,34,37,39,40,42–50,56–59] and 974 SEEG monitors (median: 43, range: 2–215) in 16 publications [18,23,27,28,35–41,51–55]. All except two studies [34,57] provided data in reference to the age of participating patients, which ranged from 2 years [18] through 69 years of age [27]. Although studies containing solely children were excluded, demographic (age) data showed that children were also included throughout 7 publications in the SDG group [42,43,48,43–50,56,57], and in 11 cases in the SEEG group [18,23,27,35,36,41,51–55]. Because the age range is very similar throughout these cases and nearly all publications possess the greatest patient population, we were not able to categorically exclude them.

Sex distribution was provided throughout 16 studies with a pooled gender ratio (male/female) of 0.996 in the SEEG group, [18,23,27,28,35–41,51–55] while it was 1.294 in the SDG group, extracted from a pool of 10 articles [28,29,39,42,43,48,49,56,58,59].

5. Resective surgery

The rate of resective surgeries deriving from the SDG monitor was measured in 88.8% (95% CI: 83.3%–92.6%); (I2 = 76.99%; p < 0.001). The percentage of resective surgeries occurring in the SEEG group was 79.0% (95% CI: 70.4%–85.7%); (I2 = 72.47%; p < 0.001). Undeniably, the difference between the two groups was statistically significant (p = 0.025) (Appendix: Supplemental Digital Content 8; Fig. 1).

Following SDG interventions, the pro rata of followed surgical resections was 96.2% (95% CI: 92.4%–98.1%); (I² = 49.12%;p = 0.010), and, following the use of SEEG monitors, it was 94.9% (95% CI: 89.3%–97.6%); (I² = 80.18%;p < 0.001). The difference between the two groups was not statistically significant (p = 0.634) (Appendix: Supplemental Digital Content 9; Fig. 2).

The average follow-up time was calculated at 10.06 months in the SEEG group, while it was 18.79 months in the SDG group.

In the SDG group, the ratio of Engel I outcome was 55.9% (95% CI: 50.9%–60.8%), while the likelihood of Engel II-IV outcome was about 44.1% (95% CI: 39.2%–49.1%); (I² = 54.47%;p = 0.002). Following the use of SEEG monitors, the Engel I outcome was 64.7% (95% CI: 59.2%–69.8%), thus the Engel II-IV outcome was 35.3% (95% CI: 30.2%–40.8%); (I² = 11.86%;p = 0.318). Interestingly, the difference between seizure-free outcomes among the SEEG and SDG groups was statistically significant (p = 0.02) (Appendix: Supplemental Digital Content 3 and 10; Fig. 3).

6. Presence of MRI-detected epileptogenic lesions

6.1. Nonlesional patients

In the SDG group, 9 articles found 113 of 514 patients to be MRI-negative [42,43,45,47,48,56–59]. In the SEEG group, 6 studies stated 124 out of 354 followed patients proved nonlesional [18,23,36,37,53,54].

Following the SDG monitoring, the ratio of Engel I outcome was 54.4% (95% CI: 40.6%–67.6%), while the likelihood of the Engel II-IV outcome was 45.6% (95% CI: 32.4%–59.4%); (I² = 28.84%; p = 0.188). In the SEEG group, the pro rata of Engel I outcome was 52.0% (95% CI: 37.3%–66.3%), while the percentage of the Engel II-IV outcome was 48.0% (95% CI: 33.7%–62.7%); (I² = 62.62%; p = 0.20). The difference between seizure-free outcomes of nonlesional SEEG and SDG groups was not statistically significant (p = 0.813) (Appendix: Supplemental Digital Content 4 and 11; Fig. 4).

6.2. Lesional patients

In the SDG group, 12 articles found 505 of 622 patients exhibiting epileptogenic lesions upon the MRI [29,42–48,56–59]. In the SEEG group, 9 studies stated 160 out of 316 followed patients proved lesional [23,36–38,51,53–55].

In the SDG group, the percentage of Engel I outcome was 57.3% (95% CI: 48.7%–65.6%), while the pro-rata of Engel II-IV outcome was 42.7% (95% CI: 34.4%–51.3%);.(I² = 69.87%; p < 0.001). In the SEEG group, the ratio of Engel I outcome was 71.6% (95% CI: 61.6%–79.9%), while the likelihood of Engel II-IV outcome was 28.4% (95% CI: 20.1%–38.4%); (I² = 24.54%; p = 0.225). The difference between seizure-free outcomes in lesional SEEG and SDG groups was statistically significant (p = 0.031) (Appendix: Supplemental Digital Content 5 and 12; Fig. 5).

6.3. Temporal versus extratemporal cases

6.3.1. Temporal groups
In the SDG group, 11 publications [34,39,43–48,50,57,58] stated 362 out of 473 followed patients suffered from temporal lobe epilepsy. In the SEEG group, 6 publications [18,27,38,39,51,55] stated 108 out of 292 followed patients suffered from temporal lobe epilepsy.

In the SDG group, the ratio of Engel I outcome was 56.7% (95% CI: 51.5%–61.9%), while the proportion of Engel II-IV outcome was 43.3% (95% CI: 38.1%–48.5%); (I² = 3.167%; p = 0.412). In the SEEG group, the ratio of Engel I outcome was 73.9% (95% CI: 64.4%–81.6%), while the pro rata of the Engel II-IV outcome was 26.1% (95% CI: 18.4%–35.6%); (I² = 0.000%; p = 0.452). The difference between seizure-free outcomes was statistically significant (p = 0.002) in temporal groups following SEEG or SDG monitoring (Appendix: Supplemental Digital Content 6 and 13; Fig. 6).

6.3.2. Extratemporal groups
In the SDG group, 8 publications [34,37,40,44,45,48,57,59] stated 172 out of 274 followed patients proved to be extratemporal. In the SEEG group, 6 publications [18,27,36,37,40,53] stated 248 out of 319 followed patients suffered from extratemporal lobe epilepsy.

In the SDG group, the frequence of the Engel I outcome was 46.7% (95% CI: 36.5%–57.2%), while the proportion of Engel II-IV outcome was 53.3% (95% CI: 42.8%–63.5%); (I² = 40.761%; p = 0.107). In the SEEG group, the ratio of the Engel I outcome was 61.0% (95% CI: 51.0%–70.2%), while the likelihood of the Engel II-IV outcome was 39.0% (95% CI: 29.8%–49.0%); (I² = 26.21%; p = 0.238). The difference between seizure-free outcomes in lesional SEEG and SDG groups demonstrates a strong trend (p = 0.053) (Appendix: Supplemental Digital Content 7, 14 and 15).

Total resections

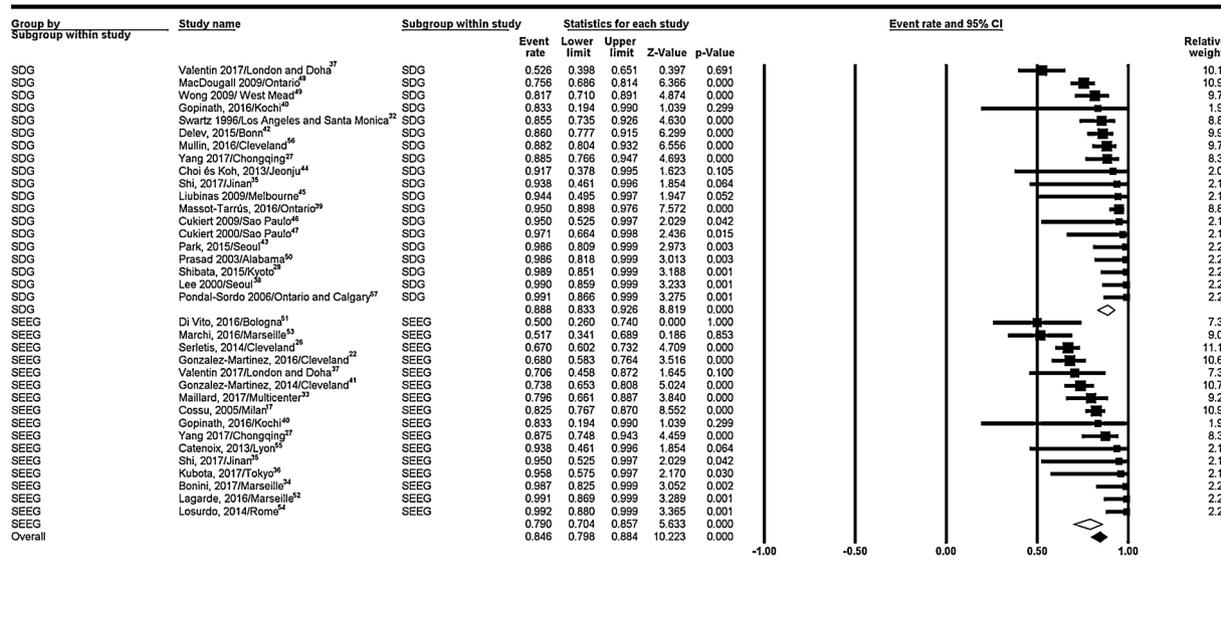| Group by Subgroup within study	Study name	Subgroup within study	Statistics for each study					Event rate and 95% CI	Relative weight
			Event rate	Lower limit	Upper limit	Z-Value	p-Value		
SDG	Valentin 2017/London and Doha[37]	SDG	0.526	0.398	0.651	0.397	0.691		10.13
SDG	MacDougall 2009/Ontario[48]	SDG	0.756	0.686	0.814	6.366	0.000		10.91
SDG	Wong 2009/ West Mead[49]	SDG	0.817	0.710	0.891	4.874	0.000		9.71
SDG	Gopinath, 2016/Kochi[40]	SDG	0.833	0.194	0.990	1.039	0.299		1.92
SDG	Swartz 1996/Los Angeles and Santa Monica[32]	SDG	0.855	0.735	0.926	4.630	0.000		8.89
SDG	Delev, 2015/Bonn[56]	SDG	0.860	0.777	0.915	6.299	0.000		9.90
SDG	Mullin, 2016/Cleveland[56]	SDG	0.882	0.804	0.932	6.556	0.000		9.70
SDG	Yang 2017/Chongqing[27]	SDG	0.885	0.766	0.947	4.693	0.000		8.33
SDG	Choi és Koh, 2013/Jeonju[44]	SDG	0.917	0.378	0.995	1.623	0.105		2.08
SDG	Shi, 2017/Jinan[35]	SDG	0.938	0.461	0.996	1.854	0.064		2.11
SDG	Liubinas 2009/Melbourne[45]	SDG	0.944	0.495	0.997	1.947	0.052		2.13
SDG	Massot-Tarrús, 2016/Ontario[39]	SDG	0.950	0.898	0.976	7.572	0.000		8.83
SDG	Cukiert 2009/Sao Paulo[46]	SDG	0.950	0.525	0.997	2.029	0.042		2.14
SDG	Cukiert 2000/Sao Paulo[47]	SDG	0.971	0.664	0.998	2.436	0.015		2.18
SDG	Park, 2015/Seoul[43]	SDG	0.986	0.809	0.999	2.973	0.003		2.20
SDG	Prasad 2003/Alabama[50]	SDG	0.986	0.818	0.999	3.013	0.003		2.20
SDG	Shibata, 2015/Kyoto[51]	SDG	0.989	0.851	0.999	3.188	0.001		2.21
SDG	Lee 2000/Seoul[38]	SDG	0.990	0.859	0.999	3.233	0.001		2.21
SDG	Pondal-Sordo 2006/Ontario and Calgary[57]	SDG	0.991	0.866	0.999	3.275	0.001		2.21
SDG			0.888	0.833	0.926	8.819	0.000		
SEEG	Di Vito, 2016/Bologna[51]	SEEG	0.500	0.260	0.740	0.000	1.000		7.31
SEEG	Marchi, 2016/Marseille[28]	SEEG	0.517	0.341	0.689	0.186	0.853		9.08
SEEG	Serletis, 2014/Cleveland[26]	SEEG	0.670	0.602	0.732	4.709	0.000		11.19
SEEG	Gonzalez-Martinez, 2016/Cleveland[22]	SEEG	0.680	0.583	0.764	3.516	0.000		10.69
SEEG	Valentin 2017/London and Doha[37]	SEEG	0.706	0.458	0.872	1.645	0.100		7.33
SEEG	Gonzalez-Martinez, 2014/Cleveland[41]	SEEG	0.738	0.653	0.808	5.024	0.000		10.76
SEEG	Maillard, 2017/Multicenter[33]	SEEG	0.796	0.661	0.887	3.840	0.000		9.26
SEEG	Cossu, 2005/Milan[17]	SEEG	0.825	0.767	0.870	8.552	0.000		10.96
SEEG	Gopinath, 2016/Kochi[40]	SEEG	0.833	0.194	0.990	1.039	0.299		1.93
SEEG	Yang 2017/Chongqing[27]	SEEG	0.875	0.748	0.943	4.459	0.000		8.36
SEEG	Catenoix, 2013/Lyon[55]	SEEG	0.938	0.461	0.996	1.854	0.064		2.13
SEEG	Shi, 2017/Jinan[35]	SEEG	0.950	0.525	0.997	2.029	0.042		2.15
SEEG	Kubota, 2017/Tokyo[36]	SEEG	0.958	0.575	0.997	2.170	0.030		2.17
SEEG	Bonini, 2017/Marseille[34]	SEEG	0.987	0.825	0.999	3.052	0.002		2.22
SEEG	Lagarde, 2016/Marseille[52]	SEEG	0.991	0.869	0.999	3.289	0.001		2.23
SEEG	Losurdo, 2014/Rome[54]	SEEG	0.992	0.880	0.999	3.365	0.001		2.23
SEEG			0.790	0.704	0.857	5.633	0.000		
Overall			0.846	0.798	0.884	10.223	0.000		

Meta Analysis

Fig. 1. Association between total numbers of resective surgeries deriving from SDG- or SEEG-monitors.

7. Discussion

In the last decade, despite presurgical evaluations consistently on the increase, the absolute and relative amount of resective epilepsy surgery remained stable or rather decreased, [60,61] causing an augmenting demand for performing preoperative intracranial recordings (SDG or SEEG). There is a marked trend towards the growing numbers of drug-resistant epileptic patients and increasing epilepsy duration prior to referral in regard to presurgical assessment [60–62], thus the importance of iEEG techniques appears to be continuously on the increase. This systematic review highlights surgical outcomes originating clearly from either SDG or SEEG to synthetize the resume of iEEG outcome studies.

We found a statistically higher likelihood of resective surgeries in the SDG group (88.8%) as compared to the SEEG (79%) group, with a very high follow-up proportion (a tor about 95–96%) in both groups. This may be due to the explicit demand of resective surgery to be performed immediately following SDG-monitoring. In the SDG group, seizure-free outcome was 55.9%, while it was 64.7% in the SEEG group; the difference was statistically significant. Supposedly, the smaller
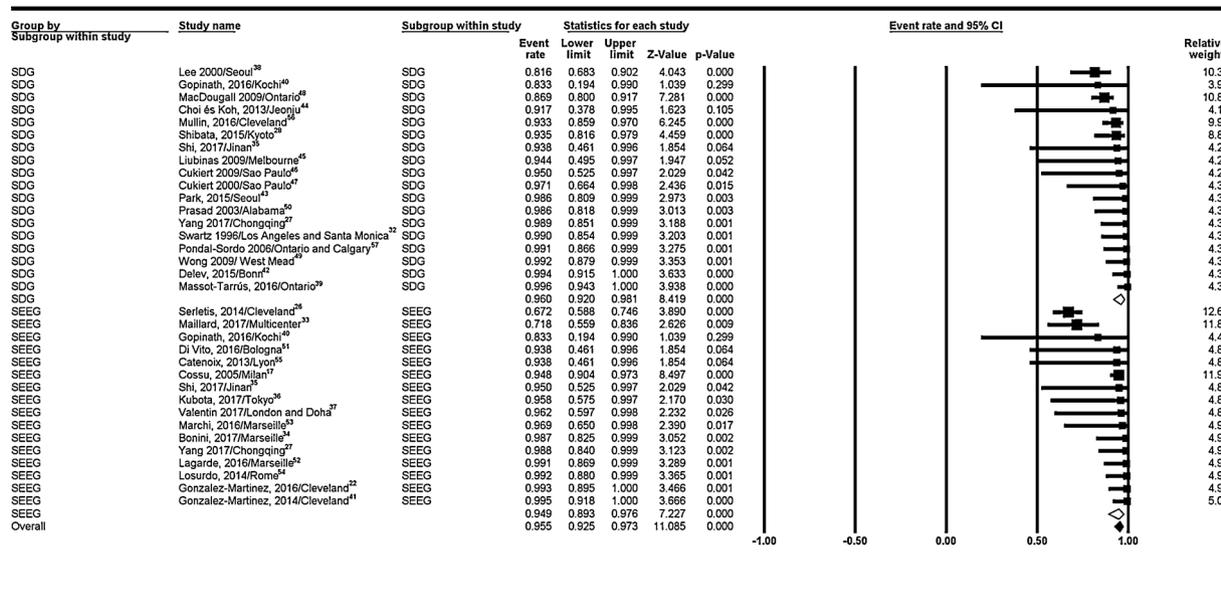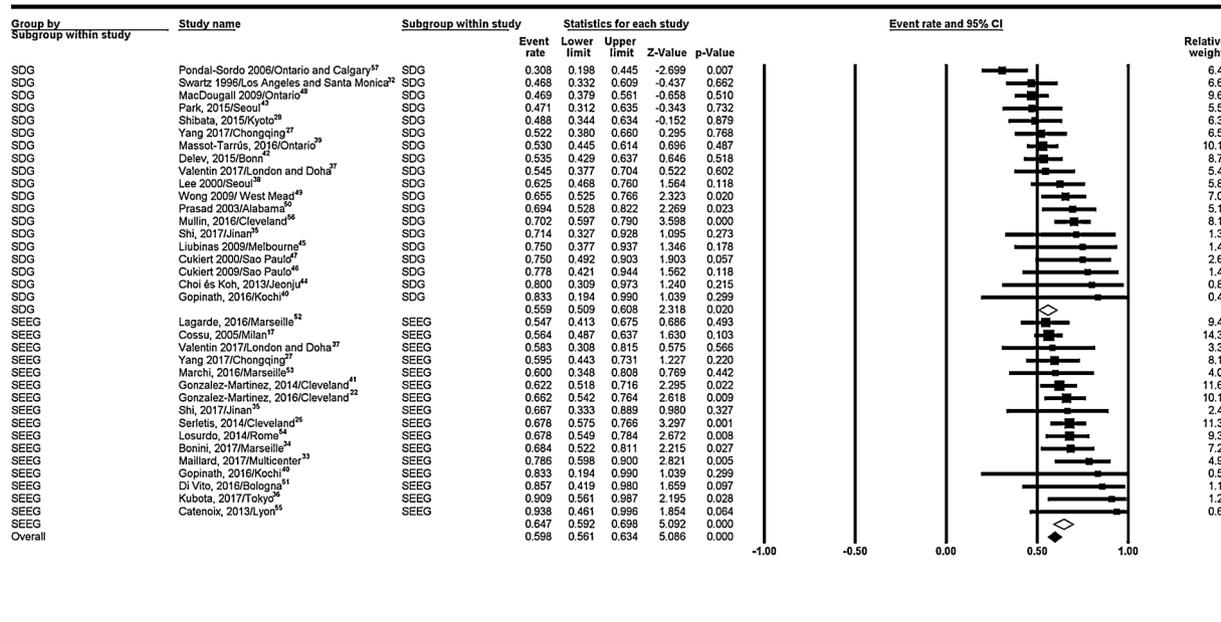
Followed resections

Group by Subgroup within study	Study name	Subgroup within study	Statistics for each study					Event rate and 95% CI	Relative weight
			Event rate	Lower limit	Upper limit	Z-Value	p-Value		
SDG	Lee 2000/Seoul[38]	SDG	0.816	0.683	0.902	4.043	0.000		10.30
SDG	Gopinath, 2016/Kochi[40]	SDG	0.833	0.194	0.990	1.039	0.299		3.91
SDG	MacDougall 2009/Ontario[48]	SDG	0.869	0.800	0.917	7.281	0.000		10.83
SDG	Choi és Koh, 2013/Jeonju[44]	SDG	0.917	0.378	0.995	1.623	0.105		4.16
SDG	Mullin, 2016/Cleveland[56]	SDG	0.933	0.859	0.970	6.245	0.000		9.99
SDG	Shibata, 2015/Kyoto[51]	SDG	0.935	0.816	0.979	4.459	0.000		8.88
SDG	Shi, 2017/Jinan[35]	SDG	0.938	0.461	0.996	1.854	0.064		4.22
SDG	Liubinas 2009/Melbourne[45]	SDG	0.944	0.495	0.997	1.947	0.052		4.24
SDG	Cukiert 2009/Sao Paulo[46]	SDG	0.950	0.525	0.997	2.029	0.042		4.25
SDG	Cukiert 2000/Sao Paulo[47]	SDG	0.971	0.664	0.998	2.436	0.015		4.31
SDG	Park, 2015/Seoul[43]	SDG	0.986	0.809	0.999	2.973	0.003		4.35
SDG	Prasad 2003/Alabama[50]	SDG	0.986	0.818	0.999	3.013	0.003		4.35
SDG	Yang 2017/Chongqing[27]	SDG	0.989	0.851	0.999	3.188	0.001		4.36
SDG	Swartz 1996/Los Angeles and Santa Monica[32]	SDG	0.990	0.854	0.999	3.203	0.001		4.36
SDG	Pondal-Sordo 2006/Ontario and Calgary[57]	SDG	0.991	0.866	0.999	3.275	0.001		4.36
SDG	Wong 2009/ West Mead[49]	SDG	0.992	0.879	0.999	3.353	0.001		4.37
SDG	Delev, 2015/Bonn[56]	SDG	0.994	0.915	1.000	3.633	0.000		4.37
SDG	Massot-Tarrús, 2016/Ontario[39]	SDG	0.996	0.943	1.000	3.938	0.000		4.38
SDG			0.960	0.920	0.981	8.419	0.000		
SEEG	Serletis, 2014/Cleveland[26]	SEEG	0.672	0.588	0.746	3.890	0.000		12.69
SEEG	Maillard, 2017/Multicenter[33]	SEEG	0.718	0.559	0.836	2.626	0.009		11.84
SEEG	Gopinath, 2016/Kochi[40]	SEEG	0.833	0.194	0.990	1.039	0.299		4.46
SEEG	Di Vito, 2016/Bologna[51]	SEEG	0.938	0.461	0.996	1.854	0.064		4.82
SEEG	Catenoix, 2013/Lyon[55]	SEEG	0.938	0.461	0.996	1.854	0.064		4.82
SEEG	Cossu, 2005/Milan[17]	SEEG	0.948	0.904	0.973	8.497	0.000		11.92
SEEG	Shi, 2017/Jinan[35]	SEEG	0.950	0.525	0.997	2.029	0.042		4.86
SEEG	Kubota, 2017/Tokyo[36]	SEEG	0.958	0.575	0.997	2.170	0.030		4.88
SEEG	Valentin 2017/London and Doha[37]	SEEG	0.962	0.597	0.998	2.232	0.026		4.89
SEEG	Marchi, 2016/Marseille[53]	SEEG	0.969	0.650	0.998	2.390	0.017		4.92
SEEG	Bonini, 2017/Marseille[34]	SEEG	0.987	0.825	0.999	3.052	0.002		4.97
SEEG	Yang 2017/Chongqing[27]	SEEG	0.988	0.840	0.999	3.123	0.002		4.98
SEEG	Lagarde, 2016/Marseille[52]	SEEG	0.991	0.869	0.999	3.289	0.001		4.98
SEEG	Losurdo, 2014/Rome[54]	SEEG	0.992	0.880	0.999	3.365	0.001		4.99
SEEG	Gonzalez-Martinez, 2016/Cleveland[22]	SEEG	0.993	0.895	1.000	3.466	0.001		4.99
SEEG	Gonzalez-Martinez, 2014/Cleveland[41]	SEEG	0.995	0.918	1.000	3.666	0.000		5.00
SEEG			0.949	0.893	0.976	7.227	0.000		
Overall			0.955	0.925	0.973	11.085	0.000		

Meta Analysis

Fig. 2. Association between followed surgical resections after SDG- or SEEG-monitors.

Engel I

Group by Subgroup within study	Study name	Subgroup within study	Event rate	Lower limit	Upper limit	Z-Value	p-Value	Relative weight
SDG	Pondal-Sordo 2006/Ontario and Calgary[57]	SDG	0.308	0.198	0.445	-2.699	0.007	6.46
SDG	Swartz 1996/Los Angeles and Santa Monica[22]	SDG	0.468	0.332	0.609	-0.437	0.662	6.66
SDG	MacDougall 2009/Ontario[48]	SDG	0.469	0.379	0.561	-0.658	0.510	9.69
SDG	Park, 2015/Seoul[43]	SDG	0.471	0.312	0.635	-0.343	0.732	5.53
SDG	Shibata, 2015/Kyoto[28]	SDG	0.488	0.344	0.634	-0.152	0.879	6.35
SDG	Yang 2017/Chongqing[27]	SDG	0.522	0.380	0.660	0.295	0.768	6.59
SDG	Massot-Tarrús, 2016/Ontario[39]	SDG	0.530	0.445	0.614	0.696	0.487	10.17
SDG	Delev, 2015/Bonn[42]	SDG	0.535	0.429	0.637	0.646	0.518	8.79
SDG	Valentin 2017/London and Doha[37]	SDG	0.545	0.377	0.704	0.522	0.602	5.41
SDG	Lee 2000/Seoul[38]	SDG	0.625	0.468	0.760	1.564	0.118	5.88
SDG	Wong 2009/ West Mead[49]	SDG	0.655	0.525	0.766	2.323	0.020	7.06
SDG	Prasad 2003/Alabama[50]	SDG	0.694	0.528	0.822	2.269	0.023	5.18
SDG	Mullin, 2016/Cleveland[56]	SDG	0.702	0.597	0.790	3.598	0.000	8.11
SDG	Shi, 2017/Jinan[35]	SDG	0.714	0.327	0.928	1.095	0.273	1.37
SDG	Liubinas 2009/Melbourne[45]	SDG	0.750	0.377	0.937	1.346	0.178	1.43
SDG	Cukiert 2000/Sao Paulo[47]	SDG	0.750	0.492	0.903	1.903	0.057	2.61
SDG	Cukiert 2009/Sao Paulo[46]	SDG	0.778	0.421	0.944	1.562	0.118	1.48
SDG	Choi és Koh, 2013/Jeonju[44]	SDG	0.800	0.309	0.973	1.240	0.215	0.80
SDG	Gopinath, 2016/Kochi[40]	SDG	0.833	0.194	0.990	1.039	0.299	0.43
SDG			0.559	0.509	0.608	2.318	0.020	
SEEG	Lagarde, 2016/Marseille[52]	SEEG	0.547	0.413	0.675	0.686	0.493	9.42
SEEG	Cossu, 2005/Milan[17]	SEEG	0.564	0.487	0.637	1.630	0.103	14.34
SEEG	Valentin 2017/London and Doha[37]	SEEG	0.583	0.308	0.815	0.575	0.566	3.39
SEEG	Yang 2017/Chongqing[27]	SEEG	0.595	0.443	0.731	1.227	0.220	8.18
SEEG	Marchi, 2016/Marseille[53]	SEEG	0.600	0.348	0.808	0.769	0.442	4.02
SEEG	Gonzalez-Martinez, 2014/Cleveland[41]	SEEG	0.622	0.518	0.716	2.295	0.022	11.67
SEEG	Gonzalez-Martinez, 2016/Cleveland[22]	SEEG	0.662	0.542	0.764	2.818	0.009	10.13
SEEG	Shi, 2017/Jinan[35]	SEEG	0.667	0.333	0.889	0.980	0.327	2.46
SEEG	Serletis, 2014/Cleveland[26]	SEEG	0.678	0.575	0.766	3.297	0.001	11.33
SEEG	Losurdo, 2014/Rome[54]	SEEG	0.678	0.549	0.784	2.672	0.008	9.33
SEEG	Bonini, 2017/Marseille[34]	SEEG	0.684	0.522	0.811	2.215	0.027	7.22
SEEG	Maillard, 2017/Multicenter[33]	SEEG	0.786	0.598	0.900	2.821	0.005	4.94
SEEG	Gopinath, 2016/Kochi[40]	SEEG	0.833	0.194	0.990	1.039	0.299	0.57
SEEG	Di Vito, 2016/Bologna[51]	SEEG	0.857	0.419	0.980	1.659	0.097	1.14
SEEG	Kubota, 2017/Tokyo[36]	SEEG	0.909	0.561	0.987	2.195	0.028	1.20
SEEG	Catenoix, 2013/Lyon[55]	SEEG	0.938	0.461	0.996	1.854	0.064	0.64
SEEG			0.647	0.592	0.698	5.092	0.000	
Overall			0.598	0.561	0.634	5.086	0.000	

Meta Analysis

Fig. 3. Association between the ratios of Engel I outcomes calculated from followed surgical resections (overall group), after SDG- or SEEG-monitors.

MR- Engel I

Group by Subgroup within study	Study name	Subgroup within study	Event rate	Lower limit	Upper limit	Z-Value	p-Value	Relative weight
SDG	Delev, 2015/Bonn[42]	SDG	0.188	0.062	0.447	-2.289	0.022	11.87
SDG	Lee 2000/Seoul[38]	SDG	0.400	0.100	0.800	-0.444	0.657	7.33
SDG	Park, 2015/Seoul[43]	SDG	0.455	0.203	0.732	-0.301	0.763	12.68
SDG	Massot-Tarrús, 2016/Ontario[39]	SDG	0.550	0.396	0.695	0.631	0.528	21.73
SDG	MacDougall 2009/Ontario[48]	SDG	0.621	0.436	0.776	1.287	0.198	19.37
SDG	Liubinas 2009/Melbourne[45]	SDG	0.667	0.154	0.957	0.566	0.571	4.57
SDG	Shi, 2017/Jinan[35]	SDG	0.714	0.327	0.928	1.095	0.273	8.33
SDG	Cukiert 2000/Sao Paulo[47]	SDG	0.727	0.414	0.910	1.449	0.147	11.09
SDG	Mullin, 2016/Cleveland[56]	SDG	0.833	0.194	0.990	1.039	0.299	3.03
SDG			0.544	0.406	0.676	0.624	0.532	
SEEG	Marchi, 2016/Marseille[53]	SEEG	0.167	0.010	0.806	-1.039	0.299	3.48
SEEG	Cossu, 2005/Milan[17]	SEEG	0.381	0.248	0.534	-1.528	0.127	24.97
SEEG	Bonini, 2017/Marseille[34]	SEEG	0.400	0.214	0.620	-0.888	0.374	19.38
SEEG	Losurdo, 2014/Rome[54]	SEEG	0.500	0.294	0.706	0.000	1.000	19.72
SEEG	Shi, 2017/Jinan[35]	SEEG	0.667	0.333	0.889	0.980	0.327	12.05
SEEG	Gonzalez-Martinez, 2016/Cleveland[22]	SEEG	0.774	0.596	0.888	2.868	0.004	20.39
SEEG			0.520	0.373	0.663	0.259	0.796	
Overall			0.533	0.431	0.632	0.633	0.527	

Meta Analysis

Fig. 4. Association between the percentages of Engel I outcomes calculated from followed surgical resections in nonlesional patients, deriving from SDG- or SEEG-monitors.

portion of resective surgeries in the SEEG group may be due to the opportunity to avoid making a precocious decision concerning cortectomy. On the other hand, it could reflect the fact that SEEG, having a lower morbidity, is more easily performed in 'dubious cases'. This 10% difference may also appear throughout the Engel I outcomes, since the smaller proportion of patients possessing the possibility of a' not obligatory' or' urged' decision on probably unnecessary resections, resulting in better surgery outcomes.

8. Lesional versus nonlesional cases

A clear and statistically significant difference could be seen between the SDG and SEEG groups, when discussing lesional cases. In the SDG group, the Engel I outcome was 57.3%, while it was 71.6%, following the SEEG monitoring. In nonlesional cases, the difference was statistically not significant between the SDG and SEEG groups (SDG group:

54.4%, SEEG group: 52.0%). The difference observed in the lesional group may be explained in how most of the SEEG studies were published following 2014, and cranial MRI techniques, especially with 3D FLAIR extension, are still ameliorating, [63] resulting in ideally better implantation strategies and finally, better surgical outcome numbers. On the other hand, FCDs localize in most cases just below the sulcus [8] and thus they can be more easily examined using deep electrodes than grids, therefore SEEG interventions may result in a greater chance of seizure-freedom status.

9. Temporal or extratemporal comparisons

In temporal lobe epilepsy, Engel I outcome was 56.7% in SDG group, while it was 73.9% in the SEEG group. The difference between seizure-free outcomes was statistically significant.

In extratemporal cases, the Engel I outcome was 46.7% in the SDG

MR+ Engel I
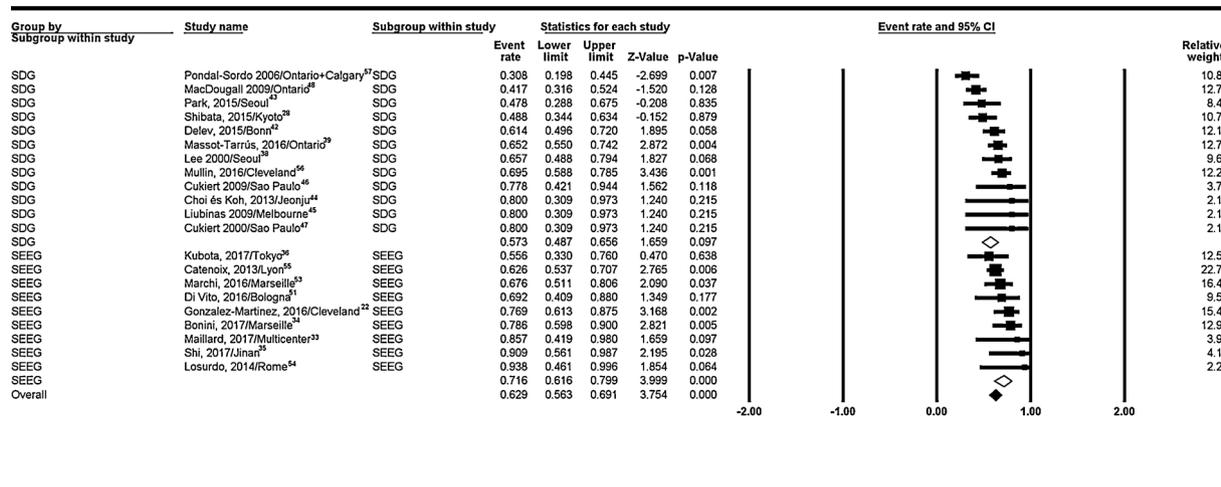
Meta Analysis

Fig. 5. Association between the rates of Engel I outcomes calculated from followed surgical resections in lesional patients, following SDG- or SEEG-monitors.

group and it was 61.0% in the SEEG group. This difference was not statistically significant (p = 0.053).

The causes in differences between the SDG and SEEG group results may be attributed to the cases discussed above. The reason of the difference between temporal and extratemporal cases (cca. 10% better outcomes in temporal group than in the extratemporal group) may be the anatomy, semiology subtypes and, most importantly, experiences collected by epilepsy centers managing an elevated number of patients with temporal lobe epilepsy, the mostly elucidated one among all subtypes of human epilepsies.

10. Limitations

The two approaches (SDG or SEEG) represent opposing explorative strategies, which is more important than the exploration tool itself. When considering the SDG, only one third of the cerebral cortex can be investigated, while the remaining two **thirds** are accessible using SEEG [20]. Ideally, both groups should undergo comparative analysis, in greater detail, in accordance with the various etiologies, the results of the pathological anatomy, the volume of the cortectomies carried out,

and the topography of the epileptogenic zones. Unfortunately, only a small percentage of utilizable studies feature such data [35,40,44,51,52,55]. To exclude this realm of potential errors, a prospective randomized study set-up is necessary in every single center using either the SEEG or SDG, with identical epileptologist(s); moreover, our study was retrospective. Another limiting condition is that the majority of the publications on SDG are much older than those on SEEG, which might result in a bias, not only for the definition of MRI negative patients, but also for the general conception of the implantation scheme, and finally, in deciding on resective surgery.

On the other hand, we decided to perform this meta-analysis, in response to the expressed demand for such data. An overwhelming majority of the studies included was published by single centers [18,23,27–29,36–38,40–58]. In these centers, the patient population may prove to be similar: drug-resistant cases without specific epileptogenic lesion upon the cranial MRI or lesional cases with discordant preoperative imagery and electroclinical results. The final output (seizure-free status) deriving from both approach (SDG or SEEG) is the same, allowing us to perform this comparison.

Temporal Engel I
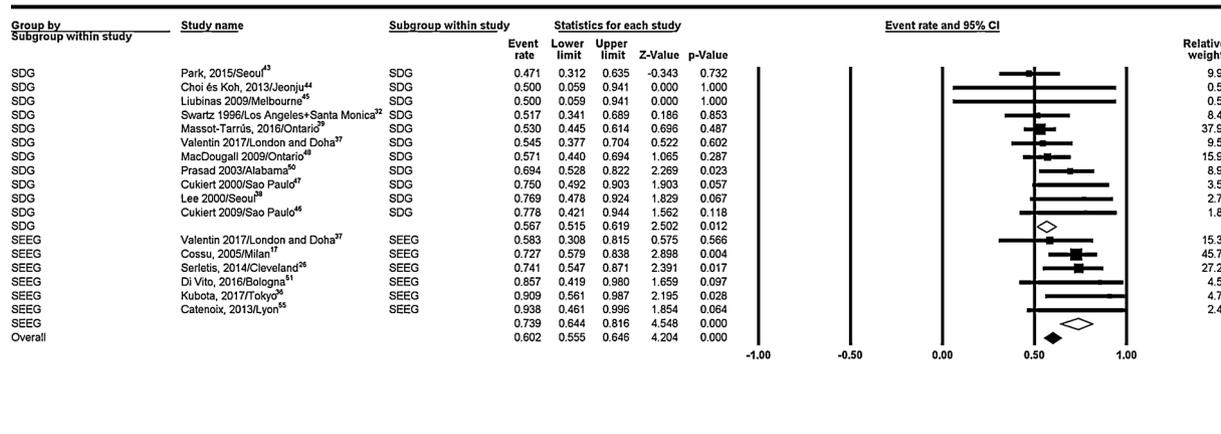
Meta Analysis

Fig. 6. Association between the ratios of Engel I outcomes calculated from followed surgical resections in temporal lobe epilepsy, deriving from SDG- or SEEG-monitors.

11. Conclusions

A significantly higher proportion of patients were selected for resective surgery following the use of the SDG monitor when collated to the SEEG group (88.8% vs 79%) with exceptionally high follow-up rates in both groups, allowing us to draw adequate conclusions due to the very small proportion of missing patients. Concerning seizure-freedom, both methods proved to be efficient. However, a significantly higher rate (almost 9%) of seizure-free outcome occurs following the use of the SEEG monitor, in regard to the SDG group (SDG group: 55.9% versus SEEG group: 64.7%).

In nonlesional cases, there is no statistically significant difference between the SDG and SEEG groups, while in lesional comparisons 14% higher Engel I outcome can be seen in the SEEG group as compared to the SDG group. In the temporal and also extratemporal lobe epilepsy patients, the proportion of seizure-free cases is clearly higher following the use of the SEEG monitor in contrast with the SDG monitor. These differences may be explained by ongoing, developmental improvements regarding contemporary cranial MRI techniques and the obviously growing experiences of neuroradiologists and also epileptologists, since most of the articles dealing with SEEG were published after 2014, while papers in the SDG group were reported in a more balanced time sequel. The other major aspect may be methodological, since lesions localized below a sulcus can be easier assessed using SEEG. Concerning the differences between temporal and extratemporal subgroups, a primary reason may be that the temporal lobe epilepsy is generally, the most known among of all epilepsy subtypes.

In conclusion, seizure-free outcomes in the SEEG group were at least non-inferior compared to those in SDG interventions.

Acknowledgements

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.seizure.2019.06.022.

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