Year: 2018

Safeness and utility of concomitant intraoperative monitoring with intraoperative magnetic resonance imaging in children - a pilot study

Dias, Sandra ; Sarnthein, Johannes ; Jehli, Elisabeth ; Neidert, Marian Christoph ; Regli, Luca ; Bozinov, Oliver

Abstract: OBJECTIVE High-field intraoperative MR (ioMRI) has become increasingly available in neurosurgery centers. There is little experience with the combination of ioMRI with intraoperative neurophysiological neuromonitoring (IONM). We provide a first series of pediatric patients undergoing brain tumor surgery with 3T ioMRI and IONM. METHODS We conducted a pilot study were we included all consecutive children operated for brain tumors between October 2013 and April 2016 where concomitant ioMRI and somatosensory evoked potentials (SEP) and motor evoked potentials (MEP) were used. All cases were retrospectively analysed concerning neuromonitoring findings and related complications. RESULTS During a period of 30 months, 17 children (mean age 8.4 years; 3 females) were operated meeting the criteria. A total of 483 IONM needles were left in place during ioMRI. Of these needles, 119 were located on the scalp, 94 above the chest, and 270 below the chest. Two complications with skin burns (first degree) were observed. In all patients, neuromonitoring was still reliable after MRI. In one case, a threshold increase for MEP-stimulation (20 mA) was necessary after ioMRI; in two cases a reduction of 50% of the SEP amplitude at the end of the surgery was observed, when compared to the values obtained before ioMRI. CONCLUSIONS The combination of ioMRI and IONM can be safely performed in the pediatric population. IONM data acquisition after ioMRI was feasible and remained reliable.

DOI: https://doi.org/10.1016/j.wneu.2018.04.123

Originally published at:
Dias, Sandra; Sarnthein, Johannes; Jehli, Elisabeth; Neidert, Marian Christoph; Regli, Luca; Bozinov, Oliver (2018). Safeness and utility of concomitant intraoperative monitoring with intraoperative magnetic resonance imaging in children - a pilot study. World Neurosurgery, 115:e637-e644.
DOI: https://doi.org/10.1016/j.wneu.2018.04.123

Title: Safeness and utility of concomitant intraoperative monitoring with intraoperative magnetic resonance imaging in children – a pilot study

Authors:

Sandra Dias[1], MD, Johannes Sarnthein[1,2], PhD, Elisabeth Jehli[1,2], MSc, Marian Christoph Neidert[1], MD, Luca Regli[1], MD, Oliver Bozinov[1], MD

[1]Neurosurgery Department, Clinical Neuroscience Center, University Hospital Zurich, University of Zurich, Zurich, Switzerland
[2]Zurich Neuroscience Center, ETH, Zurich, Switzerland

Corresponding author:
Sandra Dias, MD
Department of Neurosurgery, University Hospital Zurich, University of Zurich, Zurich, Switzerland Frauenklinikstrasse 10 - CH-8091 Zurich
Tel: +41-43-253 87 69 / +41-44-255 11 11 Fax: +41-44-255 43 87
E-mail: sandra.dias@usz.ch

KEYWORDS: Intraoperative neurophysiological monitoring • intraoperative MRI • pediatric neurosurgery • complications

Abstract word count: 225
Text word count: 2805
Number of references: 36
Number of tables and/or figures: 6
Number of videos: 0

Note: Portions of this work were previously presented in form of oral presentation at the European Association of Neurosurgical Societies Congress, Venice, Italy, October 2017 and at the "68. Annual Meeting of the German Society of Neurosurgery/ 7. Joint Meeting with the British Society of Neurosurgery ", Magdeburg, Germany, May 2017.

ABSTRACT

Objective: High-field intraoperative MR (ioMRI) has become increasingly available in neurosurgery centers. There is little experience with the combination of ioMRI with intraoperative neurophysiological neuromonitoring (IONM). We provide a first series of pediatric patients undergoing brain tumor surgery with 3T ioMRI and IONM.

Methods: We conducted a pilot study were we included all consecutive children operated for brain tumors between October 2013 and April 2016 where concomitant ioMRI and somatosensory evoked potentials (SEP) and motor evoked potentials (MEP) were used. All cases were retrospectively analysed concerning neuromonitoring findings and related complications.

Results: During a period of 30 months, 17 children (mean age 8.4 years; 3 females) were operated meeting the criteria. A total of 483 IONM needles were left in place during ioMRI. Of these needles, 119 were located on the scalp, 94 above the chest, and 270 below the chest. Two complications with skin burns (first degree) were observed. In all patients, neuromonitoring was still reliable after MRI. In one case, a threshold increase for MEP-stimulation (20 mA) was necessary after ioMRI; in two cases a reduction of 50% of the SEP amplitude at the end of the surgery was observed, when compared to the values obtained before ioMRI.

Conclusions: The combination of ioMRI and IONM can be safely performed in the pediatric population. IONM data acquisition after ioMRI was feasible and remained reliable.

KEYWORDS: Intraoperative neurophysiological monitoring • intraoperative MRI • pediatric neurosurgery • complications

INTRODUCTION

Brain surgery in eloquent cortical areas or near important white matter tracts carries a high risk for new neurological deficits. One way of monitoring eloquent structures is intraoperative neurophysiological monitoring (IONM) of the pyramidal and corticobulbar pathways [1]. Transcranial motor-evoked potential (MEP) monitoring is based on transcranial stimulation of the motor cortex with signal recording on target muscles of the extremities. Amplitude changes to the baseline threshold, or change of waveform provides a feedback of the integrity of cortical-spinal tracts [2, 3]. In younger children, the incomplete maturation of the motor system may interfere with IONM recordings and their interpretation [4-6]. In children, the reproducibility of MEP and their threshold intensity tends to increase with age [7, 8]. There is a clear correlation between intraoperative changes on the MEP and postoperative neurological deficits [9]. Therefore, intraoperative neuromonitoring has been used in the pediatric population for decades.

The benefit of high-field intraoperative magnetic resonance imaging (ioMRI) in the treatment of intracranial lesions lead to its increased use[10]. The use of ioMRI can increase the extent of resection and can therefore contribute to improved overall survival rates [11-13] .Recent studies also corroborated the safeness of this technique in the pediatric population [11, 13].

The previously demonstrated safeness's of leaving IONM cables in situ during ioMRI, supports the feasibility of using both techniques simultaneously [14-16]. Following a "maximum safe resection" concept, we believe that the combined use of ioMRI and IONM can further increase the extent of resection and improve safeness at the same time. In the current study we investigate the stability of MEP and SEP after ioMRI. Particularly in the pediatric population, as this can be different to adults due to the delayed maturation of the nervous system.

PATIENTS AND METHODS

Patient selection

We prospectively included all consecutive paediatric patients from October 2013 to April 2016, who were operated by the last author for eloquent lesions requiring somatosensory evoked potentials (SEP) and motor evoked potentials (MEP), and in which concomitant ioMRI was acquired. Patient data was collected and analysed retrospectively. The study was approved by the institutional ethics review board (Kantonale Ethikkommission KEK-ZH-2012-0212). An informed consent was obtained before surgery for all patients, in which parents were also informed about the possible complications related to ioMRI. The selection criteria resulted in a series of 17 consecutive surgical procedures in 17 patients (mean age 8.4 years, range 26 months to 14 years, 3 females). Some patients were also part of the cohort of our previous study [16], though the specific pediatric IONM results are only presented here. Patient characteristics, tumor histology and location, and the neuromonitoring data are summarized in Table 1 and Figure 1.

Anaesthesia management

Anaesthesia was induced according to our standard protocol for neurosurgical interventions with intravenous application of Propofol (2-3 mg/kg) and Fentanyl (2-3 µg/kg). Atracurium (0.5 mg/kg) was administered in order to facilitate intratracheal intubation. During the surgical procedure, anaesthesia was maintained with Propofol 10-15 mg/kg/h and Remifentanil (0.1-0.2 µg/kg/min). Inhalational agents and neuromuscular blockers were avoided. The use of this anaesthesia protocol is similar to that of other groups[17, 18].

Intraoperative neurophysiological monitoring with concomitant ioMRI

We use NORAS 8 channels head coils (NORASMRI products,Hochberg,Germany), on a 3-Tesla Siemens Skyra VD13 (Siemens, Erlangen, Germany). IONM was performed using the ISIS system (inomed Medizintechnik GmbH, Emmendingen, Germany; www.inomed.com).

On the scalp, transcranial electric stimulation for MEP and SEP recording was performed with straight Platinum/Iridium needles (0.4 x 12-mm, inomed Medizintechnik GmbH) to avoid image distortions [15]. To prevent possible bite injuries due to the electric stimulation of the jaw muscles, a roll of gauze was placed into the mouth. Needles on the scalp were fixed with skin staplers. Special care was taken so that energy transfer from the radio-frequency (RF) fields of the MRI to the cables would not cause thermal injuries, which are most likely at the electrode tip[16] (Figure 2). In an experimental ex vivo setting, electrodes had been tested in the MR for image distortions on a phantom [15] and for heating induced by the radio-frequency coils [16]. For electrode cables that would remain within the MR-magnet, gauze pads were placed between the skin and electrode cables in order to decrease the area of contact, to avoid loops of electrical current, and to reduce potential heat transmission from the cable to the skin during the MRI scan. Cables were aligned straight along the axis of the MRI-magnet to minimize energy transfer from the RF fields, which is maximal at the edges of the head coil.

Somatosensory stimulation for SEP and recording of muscle responses of MEP was performed with straight subdermal needle electrodes (non-insulated stainless steel, 0.4 x 12 mm Neuroline twisted pair, Ambu, Ballerup, Denmark, www.ambu.com). Electrodes were placed at the medianus and tibialis nerve for SEP, and for MEP in the thenar muscles of the hand and the flexor hallucis brevis muscle of the foot. Again, cables were aligned straight along the axis of the MRI-magnet.

Baseline values for SEP and MEP were set after skin incision and before dura opening. For SEP, a > 50% drop in amplitude within minutes was considered significant [19]. For MEP, a warning was issued if the stimulation threshold had to be elevated by > 20 mA or if the response amplitude dropped by > 50% [3, 17, 20].

Skin Burns

Skin burns were classified in well described and accepted four degrees, according to how deeply into the epidermis or dermis the lesion extended, with the correspondent clinical characteristics and follow-up [21]. For example, a first degree skin burn heals within 1 week and does not leave a scar.

Intraoperative 3T MR-imaging (ioMRI)

In all surgical interventions, we followed a three steps ioMRI checklist to assure the safeness of the patient during the entire procedure. The first step was made before sterile draping of the patient, so that appropriate anaesthetic devices, draping and monitoring can be assured. The second step took place before intra-operative MRI, during draping for transfer, in which all metal objects that needed to be used during surgery (eg. navigation star, metalized pad of the drape) were counted and compared to the initial settings and then removed. The last check was performed after draping for transfer in ioMRI, assuring that the head holder and the other devices (eg. anaesthesia, OR table) are properly installed and the patient can be given as “free” for MRI. After the last checklist, the patients were transferred to an adjacent-room – one door separating it from the operation theatre - and shifted into the MRI bore (3T Magneton, www.healthcare.siemens.de). Electrodes were left in place during MRI-scan. The time between temporary closure of the dura before the scan and reopening the dura to proceed with surgery was about one hour. Only 1 scan was performed during each surgical procedure.

Neurological outcome

The neurological outcome of the patients was recorded prospectively in the patient registry of the neurosurgery department [22].

RESULTS

Number of electrodes left in ioMRI

A total number of 483 electrodes were placed and were left in place during the ioMRI scan. Of these electrodes, 119 (25%) were placed on the scalp, 94 (20%) were placed in the body above the chest and thus in the proximity of the RF-coil during the ioMRI scan, and 270 (55%) were placed in the body below the chest.

Time course of MEP stimulation

Figure 3 shows the MEP stimulation intensity for each patient at different time points during surgery. For two patients, the stimulation intensity increased above the threshold of 20 mA and a warning was issued to the surgeon before the MRI-scan. In 13/17 surgeries MEP was recorded post-MRI. In the remaining 4 surgeries, MRI showed that the aim of resection was reached and therefore MEP was not continued. Interestingly, after the MRI-scan, in 2 patients the stimulation intensity could be reduced.

In five patients, a smaller stimulation intensity after ioMRI lead to the same motor response compared to pre-ioMRI responses. In one patient, we lost the MEP during surgery despite a maximum MEP stimulation with 120 mA. Unfortunately, MEPs were not retested after the ioMRI. SEP were stable during the whole procedure. There was no clinical effect or hemiparesis on this child postoperatively. In this case, we assume subdural air collection to be the cause for reduced MEPs before the ioMRI. In another case, a threshold increase for MEP-stimulation (20 mA) was necessary after ioMRI, however without any clinical correlation.

Time course of SEP recording

Figure 4 shows the time course of the SEP amplitude during surgery. In general, we observed a gradual reduction of response amplitude over time. The reduction never reached the 50% warning criterion. In 2 patients SEP was not continued after the MR-scan because the goal of resection was reached and SEP recording not continued. Interestingly, in 6/13 patients the SEP amplitude was larger after the MR-scan than before the MR-scan.

Time of warnings issued and resection after ioMRI

In 7/17 surgeries, IONM issued a warning. Of these, 4 were issued before the ioMRI scan and 3 after the ioMRI scan. At the time of warnings, the state of the surgical procedure and anaesthesia were analysed and resection proceeded. No patient suffered any paresis after surgery, so all warnings let to safe surgery in time.

In 71% (12/17) of the patients, tumor resection proceeded after ioMRI. In 24% (4/17) patients, ioMRI showed complete tumor resection. After a last intraoperative inspection, no further resection was performed. In 1 patient, even though ioMRI revealed residual tumor, due to its infiltrative character at the level of the cerebellar pontine angle and good IONM records, the decision was made not to resect further.

Outcome

One patient (no. 5) presented a significant reduction of SEP response, so as from the MEP amplitude at the beginning of the surgery, which correlated thereafter with a motor-sensitive hemi-syndrome. Nevertheless, ioMRI did not interfere with the neuromonitoring measurements. Apart from this case, no other cases with a transient new motor deficit of mechanical or vascular origin were reported.

Complications observed

In this series, two patients (Pat. no. 8 and 17) developed a skin burn (first degree) at the shoulder (Figure 5) while using SEPs and MEPs in combination with ioMRI. During clinical follow-up no long-term complications were observed, with good skin healing and absence of scarring in the two cases.

DISCUSSION

Value of ioMRI

The extent of tumor resection can influence the prognosis of a patient[12]. Therefore, ioMRI devices are more often used within neurosurgical departments with the purpose to achieve higher rates of “complete-safe resection”. It has been shown that the extent of surgical resection for some tumor entities has an influence on the prognosis[23, 24]. This takes up a special relevance in pediatric oncological neurosurgery. In the particular case of low-grade gliomas, children operated electively with ioMRI achieved a significant better surgical outcome and progression free survival, when a complete resection was aimed for [25].

Value of IONM

The use of IONM during tumor resections in eloquent areas is well established - the feedback provided to the surgeon enables a better extent of resection with the possibility of preventing new neurological deficits [26-31]. False-negative MEP results, in which new motor deficits appear besides normal intraoperative recordings are usually rare and appear to be more related with peri-lesional edema, or bleeding into the resection cavity [28, 31-33] . Nevertheless, factors as inadequate stimulation (e.g. very high intensity, not appropriate electrodes position), or vascular-dynamic alterations may induce changes in the waveform or demand a higher stimulation [33]. The experience obtained from large series of IONM during spine deformity surgeries in children detected about 5% of true positives findings and those with postoperative new neurological deficits [34, 35]. Kundnani et al[35] demonstrated that the combined use of SEPs und MEPs during spinal cord deformity surgery can achieve a sensitivity and specificity of 100%. Therefore, the safeness of this method, together with the ability to predict and avoid new neurological complications had led to the implementation of multimodality monitoring (SEPs and MEPs) as standard of care [35]. Nevertheless it is important to be aware of the “anesthetic fade” described in the literature in which MEP responses may decline over the duration of surgery, despite stable anesthetic level, so as of other physiologic parameters, as it can conduct to false positive findings [36].

Concurrent use of IONM and ioMRI

For surgeries that require both IONM and ioMRI, in principle the IONM needles could

be removed before moving the patient into the ioMRI. This would avoid all possible problems of the needles. However, IONM is usually very important during the last stage of resection when the surgeon has to decide on the limits of resection. This stage of resection is likely to occur after ioMRI. Therefore, the IONM needles have to be in place after ioMRI. A second placement of needles after ioMRI is not possible because of the sterility requirements. Consequently, IONM needles have to stay in place during ioMRI and the risk of the scan has to be minimized.
We use a 3 Tesla MRI. In case other centers have a 1.5 Tesla MRI, we assume, that based on the lower magnetic field of a 1.5 Tesla MRI, the rate of complications would be similar or inferior to the ones herein presented.

The detailed analysis in a pediatric population for combined use of both techniques has not been published so far. Our series demonstrated the relatively safe use of concomitant ioMRI and neuromonitoring in children operated for brain tumours. Sarnthein et al [16] have reported the one skin burn as a complication due to the placement of electrodes during MRI for a mixed population. In that published series, one complication was a pediatric case, which motivated us to conduct this study. In this present series of 483 placed needles left during ioMRI, another first degree skin burn on the level of the shoulder was observed, in addition to the one that has been previously reported [16].
After the first case, we decided not to place needles at the level of the shoulder, as this is right outside the zone where the head coil has the highest RF field. Unfortunately, this information was not adequately communicated internally and the same skin burn happened again. Of course, this is now highly regarded in our daily practice. Our complication rate is still under 0.4%, which in our opinion is acceptable given the benefits provided by the concomitant use of both techniques; and a needle will not be placed anymore near the should or the edge of the coil. Now we place the needles at the level of the hip, and no similar skin burn has been observed. Moreover, new MRI approved needles were introduced to the market recently.

IONM recordings remained stable after ioMRI with no need of increasing stimulation superior to 20mA in case of MEPs or a decrease superior to 50% on the SEPs amplitude being documented. The decrease in MEPs threshold with age, previously observed by Garvey et al [4], was also partially observed in our series. Slight recording variations were observed, e.g. decrease in the stimulation threshold for MEPs after ioMRI. The changes observed, could have been related to modifications in anaesthesia management, as not only the anaesthetics (and other drugs used during surgery), but also the general unconsciousness state and cardiovascular function of the patient, may influence evoked potentials - as they should be interpreted in the context of synaptic modifications[18]. Furthermore, neuromonitoring remained reliable directly after ioMRI, with no false negative results being observed in this series.

Limitations

One limitation of our study is the prospective but not randomized protocol, as children were prospectively included on this study but not in a randomized fashion. As the main purpose of the study was to access whether the concomitant use of both technics is safe (proof of safeness and concept). The other limitation is the small number of children included so far, but the number of needles is high enough for a statistical evaluation. Our complication rate is low and could have been lower with proper internal communication after the first complication case occurred. It is now a major point in our checklists for ioMRI, which were implanted during the time of this study. This concomitant use has to be followed prospectively in the future until higher pediatric caseload with stronger data is available. The eligibility to do so is warranted by our first report on this regard.

CONCLUSIONS

The combination of intraoperative magnetic resonance imaging and intraoperative neuromonitoring can be safely performed in the paediatric population in the demonstrated setting. IONM data recorded after ioMRI remained reliable.

DISCLOSURE

The used neuromonitoring cables are not MRI certified and this study was investigated “off-label” with adequate prior ethical approval (KEK-ZH-2012-0212).

The Department of Neurosurgery has a consultant agreement with Siemens.

ACKNOWLEDGEMENTS

The authors thank Elvira Ciessynna for providing the readings of the IONM recordings.

TABLES

Table 1. Patient characteristics and MEP and SEP readings. Values were obtained before MRI (for MEP), at the beginning of surgery (for SEP) and at the end of surgery.

FIGURES

Figure 1. Preoperative MRI. The location of the tumor lesion is indicated by blue arrows.

Figure 2. Needle placement for concomitant IONM and ioMRI. Needle electrodes on the scalp. Cables from the scalp and face are isolated from the skin with gauze pads and aligned along the axis of the bore of the magnet.

Figure 3. MEP stimulation intensity during the course of surgery.

Figure 4. SEP response amplitude during the course of surgery.

Figure 5. Skin burn (first degree) on the left shoulder of a 3-years old child after MRI.

References

1. Bozinov, O., M.A. Grotzer, and J. Sarnthein, *Intraoperative Monitoring of Facial Nerve Motor-Evoked Potentials in Children.* World Neurosurg, 2015. **84**(3): p. 786-94.
2. Cheng, J.S., et al., *Intraoperative changes in transcranial motor evoked potentials and somatosensory evoked potentials predicting outcome in children with intramedullary spinal cord tumors.* J Neurosurg Pediatr, 2014. **13**(6): p. 591-9.
3. Szelenyi, A., et al., *Intraoperative motor evoked potential alteration in intracranial tumor surgery and its relation to signal alteration in postoperative magnetic resonance imaging.* Neurosurgery, 2010. **67**(2): p. 302-13.
4. Garvey, M.A., et al., *Cortical correlates of neuromotor development in healthy children.* Clin Neurophysiol, 2003. **114**(9): p. 1662-70.
5. Chen, X., et al., *Success rate of motor evoked potentials for intraoperative neurophysiologic monitoring: Effects of age, lesion location, and preoperative neurologic deficits.* Journal of Clinical Neurophysiology, 2007. **24**(3): p. 281-285.
6. Szelenyi, A., A. Bueno de Camargo, and V. Deletis, *Neurophysiological evaluation of the corticospinal tract by D-wave recordings in young children.* Childs Nerv Syst, 2003. **19**(1): p. 30-4.
7. Heinen, F., et al., *Fast corticospinal system and motor performance in children: conduction proceeds skill.* Pediatr Neurol, 1998. **19**(3): p. 217-21.
8. Nezu, A., et al., *Magnetic stimulation of motor cortex in children: Maturity of corticospinal pathway and problem of clinical application.* Brain & Development, 1997. **19**(3): p. 176-180.
9. Quinones-Hinojosa, A., et al., *Changes in transcranial motor evoked potentials during intramedullary spinal cord tumor resection correlate with postoperative motor function.* Neurosurgery, 2005. **56**(5): p. 982-93; discussion 982-93.
10. Neidert, M.C., et al., *The influence of intraoperative resection control modalities on survival following gross total resection of glioblastoma.* Neurosurg Rev, 2016. **39**(3): p. 401-9.
11. Giordano, M., et al., *Intraoperative magnetic resonance imaging in pediatric neurosurgery: safety and utility.* J Neurosurg Pediatr, 2017. **19**(1): p. 77-84.
12. Senft, C., et al., *Influence of iMRI-guidance on the extent of resection and survival of patients with glioblastoma multiforme.* Technol Cancer Res Treat, 2010. **9**(4): p. 339-46.
13. Smith, H., et al., *Correlation between intraoperative ultrasound and postoperative MRI in pediatric tumor surgery.* Journal of Neurosurgery-Pediatrics, 2016. **18**(5): p. 578-584.
14. Szelenyi, A., T. Gasser, and V. Seifert, *Intraoperative neurophysiological monitoring in an open low-field magnetic resonance imaging system: clinical experience and technical considerations.* Neurosurgery, 2008. **63**(4 Suppl 2): p. 268-75; discussion 275-6.
15. Cornaz, F., et al., *Compatibility of intraoperative 3T MR imaging and intraoperative neurophysiological monitoring.* Clin Neurophysiol, 2015. **126**(1): p. 218-20.
16. Sarnthein, J., et al., *Prevalence of Complications in Intraoperative Magnetic Resonance Imaging Combined with Neurophysiologic Monitoring.* World Neurosurg, 2016. **93**: p. 168-74.
17. Fulkerson, D.H., et al., *Intraoperative monitoring of motor evoked potentials in very young children.* J Neurosurg Pediatr, 2011. **7**(4): p. 331-7.

18. Sloan, T., *Anesthesia and intraoperative neurophysiological monitoring in children.* Childs Nerv Syst, 2010. **26**(2): p. 227-35.
19. Nuwer, M.R., ed. *Intraoperative Monitoring of Neural Function*. Handbook of Clinical Neurphysiology, ed. J.R. Daube and F. Mauguière. Vol. 8. 2008, Elsevier: Amsterdam.
20. Sarnthein, J., et al., *Motor-evoked potentials (MEP) during brainstem surgery to preserve corticospinal function.* Acta Neurochir (Wien), 2011. **153**(9): p. 1753-9.
21. Toussaint, J. and A.J. Singer, *The evaluation and management of thermal injuries: 2014 update.* Clin Exp Emerg Med, 2014. **1**(1): p. 8-18.
22. Sarnthein, J., et al., *A Patient Registry to Improve Patient Safety: Recording General Neurosurgery Complications.* PLoS One, 2016. **11**(9): p. e0163154.
23. McGirt, M.J., et al., *Independent association of extent of resection with survival in patients with malignant brain astrocytoma.* J Neurosurg, 2009. **110**(1): p. 156-62.
24. Safaee, M., et al., *Surgical outcomes in spinal cord ependymomas and the importance of extent of resection in children and young adults.* J Neurosurg Pediatr, 2014. **13**(4): p. 393-9.
25. Roder, C., et al., *Beneficial impact of high-field intraoperative magnetic resonance imaging on the efficacy of pediatric low-grade glioma surgery.* Neurosurgical Focus, 2016. **40**(3).
26. Sarnthein, J., et al., *[Intraoperative neurophysiological monitoring improves outcome in neurosurgery].* Praxis, 2012. **101**(2): p. 99-105.
27. Cabraja, M., et al., *Neurophysiological intraoperative monitoring in neurosurgery: aid or handicap? An international survey.* Neurosurg Focus, 2009. **27**(4): p. E2.
28. Kelleher, M.O., et al., *Predictive value of intraoperative neurophysiological monitoring during cervical spine surgery: a prospective analysis of 1055 consecutive patients.* J Neurosurg Spine, 2008. **8**(3): p. 215-21.
29. Kombos, T., et al., *Monitoring of intraoperative motor evoked potentials to increase the safety of surgery in and around the motor cortex.* J Neurosurg, 2001. **95**(4): p. 608-14.
30. Neuloh, G., U. Pechstein, and J. Schramm, *Motor tract monitoring during insular glioma surgery.* J Neurosurg, 2007. **106**(4): p. 582-92.
31. Neuloh, G., et al., *Motor evoked potential monitoring with supratentorial surgery.* Neurosurgery, 2004. **54**(5): p. 1061-70; discussion 1070-2.
32. Lee, J.J., et al., *Intraoperative monitoring of motor-evoked potentials for supratentorial tumor surgery.* J Korean Neurosurg Soc, 2014. **56**(2): p. 98-102.
33. Neuloh, G. and J. Schramm, *Are there false-negative results of motor evoked potential monitoring in brain surgery?* Cent Eur Neurosurg, 2009. **70**(4): p. 171-5.
34. Kamerlink, J.R., et al., *Major Intraoperative Neurologic Monitoring Deficits in Consecutive Pediatric and Adult Spinal Deformity Patients at One Institution.* Spine, 2010. **35**(2): p. 240-245.
35. Kundnani, V.K., et al., *Multimodal intraoperative neuromonitoring in corrective surgery for adolescent idiopathic scoliosis: Evaluation of 354 consecutive cases.* Indian Journal of Orthopaedics, 2010. **44**(1): p. 64-72.
36. Lyon, R., J. Feiner, and J.A. Lieberman, *Progressive suppression of motor evoked potentials during general anesthesia: the phenomenon of "anesthetic fade".* J Neurosurg Anesthesiol, 2005. **17**(1): p. 13-9.