Published in final edited form as:

Spine (Phila Pa 1976). 2017 March 15; 42(6): 385–393. doi:10.1097/BRS.0000000000001767.

Intraoperative Neuromonitoring for Anterior Cervical Spine Surgery:

What Is the Evidence?

Remi M. Ajiboye, MD[*], **Stephen D. Zoller, MD**[*], **Akshay Sharma, BA**[†], **Gina M. Mosich, MD**[*], **Austin Drysch**[*], **Jesse Li, BS**[*], **Tara Reza, BS**[*], and **Sina Pourtaheri, MD**[*]

[*]Department of Orthopedic Surgery, University of California–Los Angeles, Los Angeles, CA

[†]Case Western Reserve School of Medicine, Cleveland, OH

Abstract

Study Design—Systematic review and meta-analysis.

Objective—The goal of this study was to (i) assess the risk of neurological injury after anterior cervical spine surgery (ACSS) with and without intraoperative neuromonitoring (ION) and (ii) evaluate differences in the sensitivity and specificity of ION for ACSS.

Summary of Background Data—Although ION is used to detect impending neurological injuries in deformity surgery, it's utility in ACSS remains controversial.

Methods—A systematic search of multiple medical reference databases was conducted for studies on ION use for ACSS. Studies that included posterior cervical surgery were excluded. Meta-analysis was performed using the random-effects model for heterogeneity. Outcome measure was postoperative neurological injury.

Results—The search yielded 10 studies totaling 26,357 patients. The weighted risk of neurological injury after ACSS was 0.64% (0.23–1.25). The weighted risk of neurological injury was 0.20% (0.05–0.47) for ACDFs compared with 1.02% (0.10–2.88) for corpectomies. For ACDFs, there was no difference in the risk of neurological injury with or without ION (odds ratio, 0.726; confidence interval, CI, 0.287–1.833; $P = 0.498$). The pooled sensitivities and specificities of ION for ACSS are 71% (CI: 48%–87%) and 98% (CI: 92%–100%), respectively. Unimodal ION has a higher specificity than multimodal ION [unimodal: 99% (CI: 97%–100%), multimodal: 92% (CI: 81%–96%), $P = 0.0218$]. There was no statistically significant difference in sensitivities between unimodal and multimodal [68% *vs.* 88%, respectively, $P = 0.949$].

Conclusion—The risk of neurological injury after ACSS is low although procedures involving a corpectomy may carry a higher risk. For ACDFs, there is no difference in the risk of neurological

Address correspondence and reprint requests to: Remi M. Ajiboye, MD, Department of Orthopedic Surgery, University of California–Los Angeles, 1250 16th St, Suite 2100, Santa Monica, CA 90404; Remi.Ajiboye@gmail.com.

No relevant financial activities outside the submitted work.

Supplemental digital content is available for this article. Direct URL citations appearing in the printed text are provided in the HTML and PDF version of this article on the journal's Web site (www.spinejournal.com).

No funds were received in support of this work.

Level of Evidence: 3

injury with or without ION use. Unimodal ION has a higher specificity than multimodal ION and may minimize “subclinical” intraoperative alerts in ACSS.

Keywords

anterior cervical discectomy and fusion; anterior cervical spinal surgery; cervical spine; corpectomy; electrophysiological monitoring; meta-analysis; motor evoked potential; neurologic injury; neuromonitoring; somatosensory evoked potential

Neurological injuries are known complications of spine surgery. To decrease the risk of these adverse events, intraoperative neuromonitoring (ION) is used to detect impending neurological injury. Somatosensory evoked potentials (SSEPs)and motor-evoked potentials (MEPs) are the two most commonly used ION modalities to monitor spinal cord function. SSEPs monitor spinal cord function through the ascending sensory pathway whereas MEPs provide a direct measure of the corticospinal motor tract function.

Although ION has been shown to decrease the risk of neurological injury in deformity surgery, its utility in anterior cervical spine surgery (ACSS) remains controversial.[1–8] Proponents of ION for ACSS claim that it improves patient safety and functional outcome whereas opponents refute this claim by citing increased cost and the lack of correlation between ION abnormalities and postoperative neurological deficits especially with anterior cervical discectomy and fusions (ACDFs).[9–12] The goal of this meta-analysis was to (i) assess the risk of neurological injury after ACSS with and without ION and (ii) evaluate differences in the sensitivity and specificity of ION for ACSS.

MATERIALS AND METHODS

Search Strategy

A systematic search of Medline, Embase, Cochrane Reviews, SCOPUS, and Web-of-Science was performed to identify studies that reported on ION use for ACSS. The search criteria utilized were “cervical AND monitoring,” “cervical AND neuromonitoring,” “cervical AND intra-operative neuromonitoring,” “cervical AND electrophysiological monitoring,” “cervical AND motor evoked potential,” and “cervical AND somatosensory evoked potential.” The search strategy was developed to include all study designs. English-language full text manuscripts or abstracts were reviewed. After review of all relevant reports, the references of articles selected for review were further assessed to identify studies that were not captured in our initial database search.

Selection of Studies

Studies that reported ION use for ACSS were included. Studies that involved cranial surgery, posterior cervical spinal surgery, or nonspinal surgery were excluded. Case reports, studies that utilized spinal cord evoked potential only and studies that did not report patient outcomes, were also excluded.

Data Extraction

Two reviewers (R.A. and S.Z.) reviewed and extracted data from studies that fulfilled all inclusion and exclusion criteria. The following variables were extracted from each study: year of study, type of study, level of evidence, demographic data, type of surgery, indication for surgery, type of neuromonitoring modality, neuromonitoring alert criteria, risk of neurological injury, ION sensitivity, specificity, false positive rate, and false negative rate. Primary outcome measure used was neurologic injury (defined as any evidence of worsening postoperative neurologic status from baseline).

Assessment of Level of Evidence and Methodological Quality of the Studies

Two reviewers (S.P. and R.A.) conducted a quality assessment for each of the studies selected for final analysis. Level of evidence ratings were assigned to each study using the criteria set forth by Wright *et al*[13] (Table 1).[11,14–22] Quality assessment of all the selected reports was made by using the 12-point Methodological Index for Nonrandomized Studies (MINORS) criteria (Table 2,[11,14–22] Appendix A and B, http://links.lww.com/BRS/B184). This criteria has been previously reported to have high test-retest, external and internal validity, and interobserver reliability.[23] The risk of bias (RoB) of comparative studies was assessed using the Cochrane Back Review Group tool.[24] If studies met at least six of the 12 criteria, the study was regarded as low RoB. If five or less of the 12 criteria were met, the study was labeled as high RoB. For noncomparative studies, RoB was assessed using a modified 5-point assessment score as previously described.[25] Inconsistencies in methodologic quality assessment were reconciled through discussion with a third author (S.Z.).

Data Analysis

Data analysis was performed using the random-effects model with inverse variance weighting. The principal study measures were summary estimates and 95% confidence intervals (CI). Results among studies were compared with 95% CIs and corresponding forest plots. Meta-analysis was used to estimate the risk of neurological injury in procedures involving ACDF with or without corpectomy, ACDF alone, and in ACDF with and without ION. The number of adverse neurologic events was divided by the patient cohort size to determine the incidence of injury in each study. A Q statistic and I^2 value were calculated to assess for heterogeneity between individual studies in each meta-analysis group. I^2 heterogeneity less than 25% generally indicates consistent results and homogenous studies, whereas 25% to 75% indicates moderate heterogeneity, and greater than 75% indicates severe heterogeneity, as reported by Delong *et al*.[26] Bivariate analysis was performed for sensitivity and specificity of ION. Mixed-effect logistic regression was used to compare the sensitivity and specificity of unimodal and multimodal ION. A P-value of <0.05 was considered to be statistically significant.

Calculations for the meta-analysis were performed with StataMP v. 14 (StataCorp. 2015. Stata Statistical Software: Release 14. College Station, TX) and forest plots and ROC curves were generated using Review Manager v5.3 [Review Manager (RevMan) (Computer program) Version 5.3. Copenhagen: The Nordic Cochrane Centre, the Cochrane Collaboration, 2014].

RESULTS

Studies

Overall, the search yielded 121 citations of which 111 were excluded. Thirty-two duplicate studies were excluded and 60 studies were excluded because they were not spine-related based on abstract review. The full text of the remaining 29 studies was then assessed, and 19 studies were excluded with reasons, leaving the final included studies (Figure 1). Ten studies fulfilled all inclusion and exclusion criteria and were included in this systematic review.[11,14–22]

Five of the 10 studies analyzed a uniform cohort of patients undergoing ACDF alone,[11,14,16,19,21] whereas the remaining five studies analyzed patients undergoing either ACDF alone or ACDF with corpectomy (Table 1).[15,17,18,20,22] Six studies analyzed patients monitored with a unimodal technique;[11,15,16,18,19,22] five of which used SSEP,[11,15,18,19,22] and one of which used MEP[16] (Table 3).[11,14–22]

Indications for ACSS were strictly limited to myelopathy or radiculopathy in three studies,[15,16,20] whereas the remaining studies included a small percentage of patients treated for infection, tumor, trauma, and ossified posterior longitudinal ligament (Table 1).[14,17–19,21,22]

Quality Assessment of Included Studies

Two studies were published as level III evidence[19,21] and eight studies were published as level IV evidence (Table 1).[11,14–18,22] The MINORS score of the noncomparative studies ranged from 9 to 11, with an average score of 9.63 and a standard deviation (SD) of 0.74 (Table 2). The MINORS score of the comparative studies ranged from 14 to 18, with an average score of 16 and a SD of 2.83 (Table 3). All studies included in this review were of low methodologic quality but with low RoB.

Demographics

There were a total of 26,357 patients (range, 16–22,768 per study).[11,14–22] One study, drawn from a national database, had 22,768 patients.[21] Six studies reported mean patient age with a resulting weighted mean of 51.3 years and a range of 14 to 86 years.[11,14,16,18,19,22] Two studies reported the sex of their patient population, which were 52% male[22] and 45% male,[18] respectively (Table 1).

Monitoring Technique

Of the studies which used SSEP monitoring, seven used either the median nerve or ulnar nerve for upper extremity monitoring and the tibial or peroneal nerves for lower extremity monitoring.[11,14,15,18–20,22] One study used only upper extremity SSEP monitoring.[18] Two studies did not report the technique for SSEP monitoring.[17,21] Criteria for a significant alert were a decrease in amplitude of 50% or an increase in latency of 10% in three studies,[18,20,22] a 30% to 50% decrease in amplitude in one study,[14] and a 60% decrease in amplitude in one study (Table 3).[17]

Of the studies which reported their MEP monitoring technique, various combinations of the upper extremity muscle groups including abductor pollicis brevis, first dorsal interosseous, extensor carpi radialis, triceps, and deltoid were monitored, and the lower extremity muscle groups including abductor hallucis and anterior tibialis were monitored.[14,17,20] To define a significant alert, one study used a cutoff of 50% decrease in amplitude,[14] one used a cutoff of 60% decrease in amplitude over 10 minutes,[17] and one used an undefined, "significant" reduction in amplitude (Table 3).[20]

Risk of Neurological Injury

There were 49 events of neurological injury among 26,357 patients from all studies, leading to an overall unweighted risk of adverse event of 0.19% (95% CI: 0.13–0.24). Weighted per study, the overall weighted risk of neurological injury after ACSS was 0.64% (95% CI: 0.23–1.25) (Figure 2).[11,14–22] The studies demonstrated severe heterogeneity with a Q value of 47.5366 and I^2 value of 81.07%.[11,14–22] In the five studies that analyzed a uniform cohort of patients undergoing ACDF alone,[11,14,16,19,21] the weighted risk of neurological injury was 0.20% (95% CI: 0.05–0.47) compared with 1.02% (95% CI: 0.10–2.88) in studies that involved corpectomies (there is insufficient data to perform a comparative statistical analysis between both groups).[15,17,18,21,22]

Two studies compared the risk of neurological injury in ACDF patients with or without ION.[19,21] From these groups, there was no statistically significant difference in the risk of neurological injury with or without ION (OR: 0.726, 95% CI: 0.287–1.833, $P = 0.498$) (Figure 3). The studies demonstrated consistent results and homogeneity with a Q value of 0.584 and I^2 value of 0.00%.

Intraoperative Neuromonitoring Sensitivity and Specificity

Six studies reported complete data on sensitivity and specificity.[11,14,17,19,20,22] Using bivariate analysis, the pooled sensitivities and specificities of these six studies on ION for ACSS were 71% (95% CI: 48%–87%) and 98% (CI: 92%–100%), respectively (Table 4,[11,14–22] Figure 4). Weighted per study, the positive predictive value for ION in ACSS was 24.2% and the negative predictive value was 99.6%.

To compare data for unimodal *versus* multimodal ION, the six studies with complete sensitivity and specificity data were pooled using bivariate analysis.[11,14,17,19,20,22] There was high specificity in both unimodal (specificity: 99%, 95% CI: 97%–100%) and multimodal (specificity: 92%, 95% CI: 81%–96%) ION; the difference was significant ($P = 0.0218$). Both modalities had lower sensitivities, and the difference between unimodal (sensitivity: 68%, 95% CI: 39%–88%) and multimodal (sensitivity: 88%, 95% CI: 4%–100%) was not significant ($P = 0.949$) (Table 5).

DISCUSSION

Intraoperative neuromonitoring has been used since the 1970 s for spinal surgeries.[9] Before the widespread use of ION, the Stagnara wake-up test served as the only way to intraoperatively assess neurologic function.[27] ION is now used in a variety of spine surgeries including tumor resection, deformity surgery, trauma, and degenerative spine surgery.[1,28] A

substantial body of literature shows that ION can aid with early detection of neurological injuries that occur with traction, compression, or ischemia of the spinal cord during deformity correction.[29–32]

For cervical spine surgeries such as ACDF, the routine use of ION remains controversial and there is no consensus on the optimal neuromonitoring modality to use. Epstein *et al*[10] was one of the first surgeons to argue in favor of ION for ACSS. In their series, 100 patients that had cervical spine surgery with SSEPs were compared with 218 historical control patients that had no SSEPs. Four percent of the patients in the non-monitored group developed quadriplegia compared with none of the patients in the monitored group. Improved outcomes with ION in the study were attributed to early detection of impending neurological injury by SSEPs.

The study by Epstein *et al*[10] has been refuted, notably for an outdated and elevated rate of neurological injury at 4% that they published in their historical control group. Although ION is recognized to be sensitive for diagnosing potential neurological injury, a national practice guideline in 2009 gave no recommendation in support of routine use of ION for ACSS for degenerative conditions because of lack of specificity, lack of demonstrated clinical improvement, and conflicting class I evidence on ION parameters.[33] In light of these guidelines, authors have argued that ION for degenerative ACSS has little utility when examined from a medical, cost-benefit, or medico-legal standpoint.[34] Specifically, in an economic analysis study of 720 patients that had cervical decompression and reconstruction without ION, Traynelis *et al*[12] reported no persistent postoperative neurological deficits in their series. Based on their estimate, the use of ION would have cost an hourly rate of $633.32 and incurred a total of $1,024,754 in 2011 US dollars for reimbursement at the 2011 Medicare rate.

In light of this controversial topic, we sought to answer two questions. First, what is the incidence of neurological injuries after ACSS, with and without a corpectomy, and with and without ION, from the available literature? Second, what is the sensitivity and specificity of unimodal and multimodal ION for ACSS?

Through this meta-analysis, we found that there was a low rate of neurological injury after ACSS (0.63%), and lower rate after ACDF alone (0.2%), which is in agreement with the range of 0% to 4% reported in the literature.[11,17,9,35,36] Furthermore, we found that corpectomies may be higher risk with a neurological injury rate of 1.02%.

In addition, the studies examined in this analysis generally found limited utility for ION for ACDFs as there was no difference in the risk of neurological injury with or without ION. Taunt *et al*[11] reported on 163 patients that had ACDFs with continuous SSEPs. Three (1.8%) false positives were noted in which intraoperative SSEP alerts did not correlate with postoperative neurological deterioration. In a series comparing 577 monitored patients to 462 unmonitored patients that had ACDFs, Smith *et al*[19] reported no new postoperative neurological deficits in the unmonitored group compared with one deficit in the monitored group despite normal SSEP signals.

Because of the fact that SSEPs only monitor the ascending sensory pathways of the spinal cord, some authors have advocated for the additional use of MEPs to monitor the ventral corticospinal tract especially in ACSS. Lee *et al*[17] published on a series of 1445 patients that had ACSS with MEPs, SSEPs, and electromyography. Eight surgeries needed to be aborted because of persistent MEP/SSEP amplitude loss. However, none of these eight patients developed a new postoperative neurological deficit. Conversely, Li *et al*[37] did report a low sensitivity for unimodal monitoring with SSEPs (37.5%) and MEPs (62.5%), but a high sensitivity with multimodal ION (100%) with no false positive or false negative events in their retrospective series. Therefore, there have been contradictory findings from these two studies on the utility of multimodal ION for ACSS. In this study, when comparing unimodal ION with multimodal ION, there was a significantly higher specificity for detecting neurologic injury with unimodal ION. This finding demonstrates that unimodal monitoring may help minimize “subclinical” intraoperative alerts.

LIMITATIONS

There are limitations inherent to this meta-analysis as it is subject to the cumulative weaknesses of the included studies (eight level IV and two level III). This review includes predominantly retrospective studies which are considered to be of low methodologic quality. Unfortunately, there is no sufficient body of evidence in the literature involving prospective studies and randomized controlled trials. These retrospective studies were included to amass sufficient data for comparison, as only one prospective study was available in our review of the literature.[18] A recent study by Martins *et al*[38] analyzed the quality of systematic reviews in low back surgery, and found a high rate of studies that did not reach a “very good” or “excellent” rating, highlighting the difficulties inherent in reviewing the available spine literature systematically, including the challenges in identifying randomized controlled trials.

Another limitation of this study is the significant amount of heterogeneity that exists in the included studies with regards to the type of procedure (*i.e.,* ACDFs with and without corpectomy), different types of neuromonitoring modalities and techniques, and variability in criteria for defining significant ION alerts, all of which would affect the overall sensitivity and specificity of ION reported.

Lastly, not all studies provide detailed demographic data, which makes it difficult to identify a suitable population to apply the findings of this study to. Several studies included surgeries for trauma, tumor, and infection; these indications often carry worse prognosis and have different risks of neurologic injury compared with degenerative conditions. However, the percentage of patients that fell into these categories was very low.

Despite these limitations, this study provides important aggregate data, identifying needed avenues for future research that will aid in making informed choices on the indications for ION in ACSS.

CONCLUSION

The risk of neurological injury after ACSS is low. For ACDFs, there is no difference in the risk of neurological injury with or without ION use. Unimodal ION has a higher specificity than multimodal ION and may minimize “subclinical” intraoperative alerts.

References

1. Dawson EG, Sherman JE, Kanim LE, et al. Spinal cord monitoring. Results of the Scoliosis Research Society and the European Spinal Deformity Society survey. Spine. 1991; 16:S361–4. [PubMed: 1785088]
2. Diab M, Smith AR, Kuklo TR. Neural complications in the surgical treatment of adolescent idiopathic scoliosis. Spine. 2007; 32:2759–63. [PubMed: 18007257]
3. Eggspuehler A, Sutter MA, Grob D, et al. Multimodal intraoperative monitoring during surgery of spinal deformities in 217 patients. Eur Spine J. 2007; 16:S188–96. [PubMed: 17632737]
4. Forbes HJ, Allen PW, Waller CS, et al. Spinal cord monitoring in scoliosis surgery. Experience with 1168 cases. J Bone Joint Surg Br. 1991; 73:487–91. [PubMed: 1670455]
5. Kamerlink JR, Errico T, Xavier S, et al. Major intraoperative neurologic monitoring deficits in consecutive pediatric and adult spinal deformity patients at one institution. Spine. 2010; 35:240–5. [PubMed: 20081520]
6. Nuwer MR, Emerson RG, Galloway G, et al. Evidence-based guideline update: intraoperative spinal monitoring with somato-sensory and transcranial electrical motor evoked potentials*. J Clin Neurophysiol. 2012; 29:101–8. [PubMed: 22353994]
7. Resnick DK, Choudhri TF, Dailey AT, et al. Guidelines for the performance of fusion procedures for degenerative disease of the lumbar spine. Part 15: electrophysiological monitoring and lumbar fusion. J Neurosurg Spine. 2005; 2:725–32. [PubMed: 16028743]
8. Zhuang Q, Wang S, Zhang J, et al. How to make the best use of intraoperative motor evoked potential monitoring? Experience in 1162 consecutive spinal deformity surgical procedures. Spine. 2014; 39:E1425–32. [PubMed: 25387144]
9. Engler GL, Spielholz NJ, Bernhard WN, et al. Somatosensory evoked potentials during Harrington instrumentation for scoliosis. J Bone Joint Surg Am. 1978; 60:528–32. [PubMed: 670276]
10. Epstein NE, Danto J, Nardi D. Evaluation of intraoperative somatosensory-evoked potential monitoring during 100 cervical operations. Spine. 1993; 18:737–47. [PubMed: 8516704]
11. Taunt CJ Jr, Sidhu KS, Andrew SA. Somatosensory evoked potential monitoring during anterior cervical discectomy and fusion. Spine. 2005; 30:1970–2. [PubMed: 16135987]
12. Traynelis VC, Abode-Iyamah KO, Leick KM, et al. Cervical decompression and reconstruction without intraoperative neurophysiological monitoring. J Neurosurg Spine. 2012; 16:107–13. [PubMed: 22077472]
13. Wright JG, Einhorn TA, Heckman JD. Grades of recommendation. J Bone Joint Surg Am. 2005; 87:1909–10. [PubMed: 16140803]
14. Bose B, Sestokas AK, Schwartz DM. Neurophysiological monitoring of spinal cord function during instrumented anterior cervical fusion. Spine. 2004; 4:202–7.
15. Bouchard JA, Bohlman HH, Biro C. Intraoperative improvements of somatosensory evoked potentials: correlation to clinical outcome in surgery for cervical spondylitic myelopathy. Spine (Phila Pa 1976). 1996; 21:589–94. [PubMed: 8852314]
16. Gokaslan ZL, Samudrala S, Deletis V, et al. Intraoperative monitoring of spinal cord function using motor evoked potentials via transcutaneous epidural electrode during anterior cervical spinal surgery. J Spinal Disord. 1997; 10:299–303. [PubMed: 9278914]
17. Lee JY, Hilibrand AS, Lim MR, et al. Characterization of neurophysiologic alerts during anterior cervical spine surgery. Spine. 2006; 31:1916–22. [PubMed: 16924208]
18. Sebastian C, Raya JP, Ortega M, et al. Intraoperative control by somatosensory evoked potentials in the treatment of cervical myeloradiculopathy. Results in 210 cases. Eur Spine J. 1997; 6:316–23. [PubMed: 9391801]

19. Smith PN, Balzer JR, Khan MH, et al. Intraoperative somatosensory evoked potential monitoring during anterior cervical discectomy and fusion in nonmyelopathic patients—a review of 1,039 cases. Spine J. 2007; 7:83–7. [PubMed: 17197338]
20. Xu R, Ritzl EK, Sait M, et al. A role for motor and somatosensory evoked potentials during anterior cervical discectomy and fusion for patients without myelopathy: Analysis of 57 consecutive cases. Surg Neurol Int. 2011; 2:133. [PubMed: 22059128]
21. Cole T, Veeravagu A, Zhang M, et al. Intraoperative neuromonitoring in single-level spinal procedures: a retrospective propensity score-matched analysis in a national longitudinal database. Spine. 2014; 39:1950–9. [PubMed: 25202940]
22. Khan MH, Smith PN, Balzer JR, et al. Intraoperative somatosensory evoked potential monitoring during cervical spine corpectomy surgery: experience with 508 cases. Spine (Phila Pa 1976). 2006; 31:E105–13. [PubMed: 16481938]
23. Slim K, Nini E, Forestier D, et al. Methodological index for non-randomized studies (minors): development and validation of a new instrument. ANZ J Surg. 2003; 73:712–6. [PubMed: 12956787]
24. Furlan AD, Pennick V, Bombardier C, et al. 2009 updated method guidelines for systematic reviews in the Cochrane Back Review Group. Spine. 2009; 34:1929–41. [PubMed: 19680101]
25. Nellensteijn J, Ostelo R, Bartels R, et al. Transforaminal endoscopic surgery for symptomatic lumbar disc herniations: a systematic review of the literature. Eur Spine J. 2010; 19:181–204. [PubMed: 19756781]
26. DeLong WB, Polissar N, Neradilek B. Timing of surgery in cauda equina syndrome with urinary retention: meta-analysis of observational studies. J Neurosurg Spine. 2008; 8:305–20. [PubMed: 18377315]
27. Vauzelle C, Stagnara P, Jouvinroux P. Functional monitoring of spinal cord activity during spinal surgery. Clin Orthop Relat Res. 1973; 93:173–8.
28. Magit DP, Hilibrand AS, Kirk J, et al. Questionnaire study of neuromonitoring availability and usage for spine surgery. J Spinal Disord Tech V. 2007; 20:282–9.
29. Dinner DS, Luders H, Lesser RP, et al. Intraoperative spinal somatosensory evoked potential monitoring. J Neurosurg. 1986; 65:807–14. [PubMed: 3772479]
30. Bieber E, Tolo V, Uematsu S. Spinal cord monitoring during posterior spinal instrumentation and fusion. Clin Orthop Relat Res. 1988; 229:121–4.
31. Jones SJ, Edgar MA, Ransford AO, et al. A system for the electrophysiological monitoring of the spinal cord during operations for scoliosis. J Bone Joint Surg Br. 1983; 65:134–9. [PubMed: 6826615]
32. Brown RH, Nash CL Jr, Berilla JA, et al. Cortical evoked potential monitoring. A system for intraoperative monitoring of spinal cord function. Spine. 1984; 9:256–61. [PubMed: 6729590]
33. Resnick DK, Anderson PA, Kaiser MG, et al. Electrophysiological monitoring during surgery for cervical degenerative myelopathy and radiculopathy. J Neurosurg Spine. 2009; 11:245–52. [PubMed: 19769504]
34. Harel R, Knoller N, Regev G, et al. The value of neuromonitoring in cervical spine surgery. Surg Neurol Int. 2014; 5:120. [PubMed: 25140279]
35. Flynn TB. Neurologic complications of anterior cervical interbody fusion. Spine. 1982; 7:536–9. [PubMed: 7167824]
36. James WS, Rughani AI, Dumont TM. A socioeconomic analysis of intraoperative neurophysiological monitoring during spine surgery: national use, regional variation, and patient outcomes. Neurosurg Focus. 2014; 37:E10.
37. Li F, Gorji R, Allott G, et al. The usefulness of intraoperative neurophysiological monitoring in cervical spine surgery: a retrospective analysis of 200 consecutive patients. J Neurosurg Anesthesiol. 2012; 24:185–90. [PubMed: 22525331]
38. Martins DE, Astur N, Kanas M, et al. Quality assessment of systematic reviews for surgical treatment of low back pain: an overview. The spine journal: official journal of the North American Spine Society. 2016; 16:667–75. [PubMed: 26826347]

Key Points

- A systematic review and meta-analysis was performed of available literature on intraoperative neuromonitoring during ACSS.
- The overall risk of neurological injury after ACSS is low but may be higher when involving corpectomy.
- There is no difference in the risk of neurological injury with or without ION use in anterior cervical discectomy and fusions.
- Unimodal ION has a higher specificity than multimodal ION and may minimize “subclinical” intraoperative alerts.

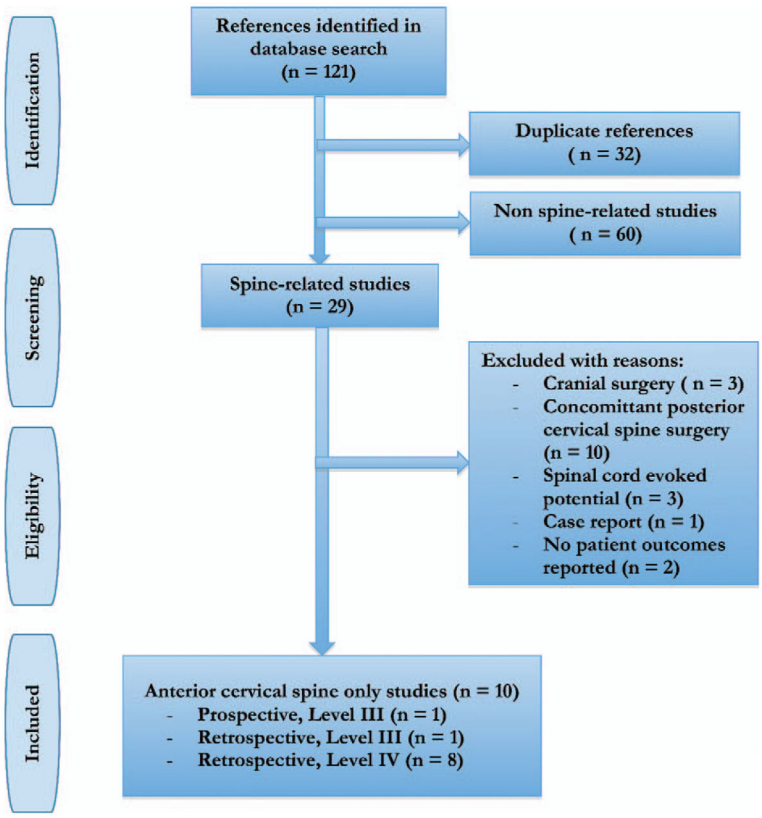
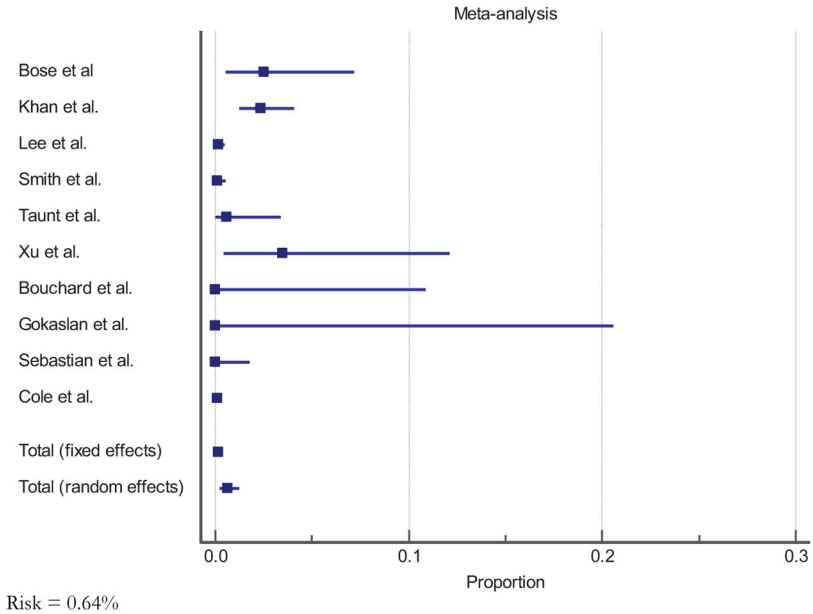


Figure 1.
Flowchart for included studies.

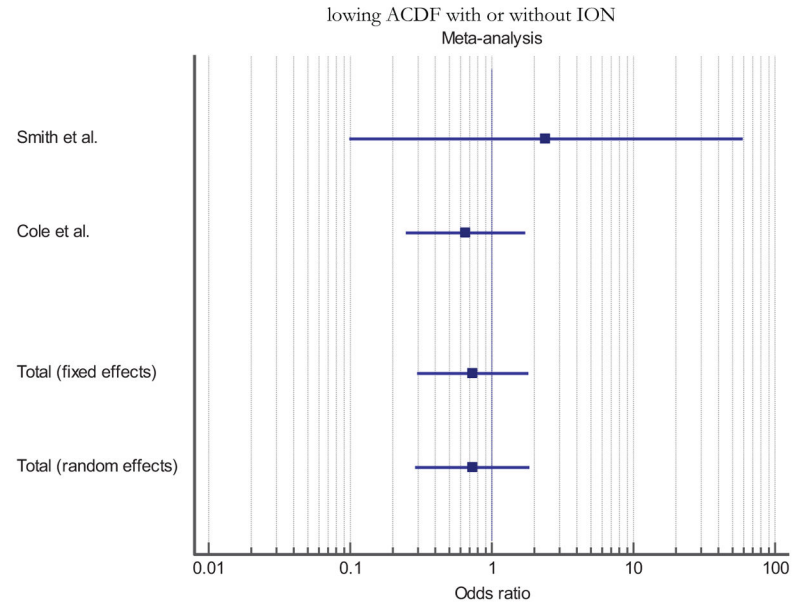


Risk = 0.64%

Test for heterogeneity

Q	47.5366
DF	9
Significance level	P < 0.0001
I^2 (inconsistency)	81.07%
95% CI for I^2	66.20 to 89.40

Figure 2.
Overall weighted risk of neurological injury after ACSS.



Odds ratio: 0.726 (CI: 0.287 - 1.833)

Test for heterogeneity

Q	0.5874
DF	1
Significance level	P = 0.4434
I^2 (inconsistency)	0.00%
95% CI for I^2	0.00 to 0.00

Figure 3.
Risk of neurological injury after ACDF with or without ION.

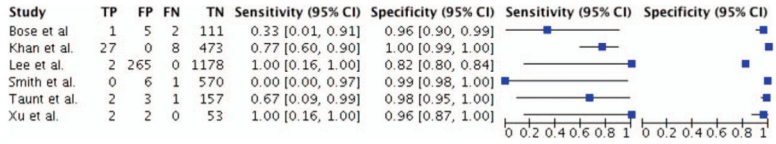


Figure 4.
Sensitivity and specificity of ION for ACSS.

TABLE 1

Study Information and Demographics

Study	Year	Type of Study	Level of Evidence	Dates of Surgery	Mean Age, Yrs (Range)	% Male	Number of Institutions	Type of Surgery	Indication for Surgery
Bose *et al*[14]	2004	Retrospective	IV	23 month period	46 (24–82)	NR	1	ACDF only	R, M, T, Tu, O
Bouchard *et al*[15]	1996	Retrospective	IV	1986–1991		NR	1	ACDF + Corpectomy	R, M
Gokaslan *et al*[16]	1997	Retrospective	IV	NR	48.6 (18–86)	NR	NR	ACDF only	R, M
Lee *et al*[17]	2006	Retrospective	IV	2000–2004	NR	NR	1	ACDF only and ACDF + Corpectomy	R, M, T, Tu, O
Sebastian *et al*[18]	1997	Prospective	IV	NR	47.2 (21 – 80)	45.5	1	ACDF only and ACDF + Corpectomy	R, M, T
Smith *et al*[19]	2007	Retrospective	III	1995–2004	NR	NR	1	ACDF only	R, T, Tu, O
Taunt *et al*[20]	2005	Retrospective	IV	1995–2002	48.6 (14–84)	NR	1	ACDF only	R, M, T, O
Xu *et al*[21]	2011	Retrospective	IV	2007–2010	47.6 +/− 11.1	NR	1	ACDF + Corpectomy	R, M
Cole *et al*[22]	2014	Retrospective	III	2006–2010	NR	NR	National database	ACDF only	NR
Khan *et al*[23]	2006	Retrospective	IV	1994–2004	55.7 (NR)	52.8	1	ACDF + Corpectomy	R, M, O

Relevant and available characteristics of each study are present.

I indicates infection; M, myelopathy; NR, not reported; O, other; R, radiculopathy; T, trauma; Tu, tumor.

Spine (Phila Pa 1976). Author manuscript; available in PMC 2018 March 15.

TABLE 2

Risk of Bias and Quality Assessment of the Noncomparative Studies

Study	Risk of Bias	MINORS Score*
Bose *et al*[14]	Low	10/16
Bouchard *et al*[15]	Low	9/16
Gokaslan *et al*[16]	Low	10/16
Lee *et al*[17]	Low	9/16
Sebastian *et al*[18]	Low	11/16
Smith *et al*[19]	Low	14/24
Taunt *et al*[20]	Low	9/16
Xu *et al*[21]	Low	9/16
Cole *et al*[22]	Low	18/24
Khan *et al*[23]	Low	10/16

*The global ideal MINORS score is 16 for noncomparative studies and 24 for comparative studies.

TABLE 3

Neuromonitoring Information

Study	Year	Monitoring Modality	Type of Monitoring	SSEP Nerve	SSEP Alert Criterion: Amplitude Decrease	SSEP Alert Criterion: Latency Increase	MEP Muscle Group	MEP Alert Criterion: Amplitude Decrease
Bose *et al*[14]	2004	Multimodal	SSEP and MEP	U, Ti	30%–50%	NR	APB, DI, TA, AH	50%
Bouchard *et al*[15]	1996	Unimodal	SSEP	M, Ti	NR	NR	NR	NR
Gokaslan *et al*[16]	1997	Unimodal	MEP/epidural electrode	NR	NR	NR	NR	NR
Lee *et al*[17]	2006	Multimodal	MEP, SSEP and EMG	NR	60%	NR	D, Tr, ECR, DI, TA, AH	60% (10 min)
Sebastian *et al*[18]	1997	Unimodal	SSEP	M	50%	10%	NR	NR
Smith *et al*[19]	2007	Unimodal	SSEP	M, U, Ti, P	50%	10%	NR	NR
Taunt *et al*[20]	2005	Unimodal	SSEP	M, Ti	NR	NR	NR	NR
Xu *et al*[21]	2011	Multimodal	SSEP and MEP	M, U, Ti	50%	10%	APB, TA, AH	“Significant reduction”
Cole *et al*[22]	2014	NR	NR	NR	NR	NR	NR	NR
Khan *et al*[23]	2006	Unimodal	SSEP	M, U, Ti, P	50%	10%	NR	NR

Relevant and available monitoring characteristics of each study are present.

AH indicates abductor hallucis; APB, abductor pollicis brevis; D, deltoid; DI, 1st dorsal interosseuous; M, median; MEP, motor evoked potential; NR, not reported; P, peroneal; SSEP, somatosensory evoked potential; TA, tibialis anterior; Ti, tibial; Tr, triceps; U, ulnar.

Spine (Phila Pa 1976). Author manuscript; available in PMC 2018 March 15.

Spine (Phila Pa 1976). Author manuscript; available in PMC 2018 March 15.

TABLE 4

Sensitivity and Specificity

Study	Year	Number of Patients	Total Incidence of Neurologic Injury (%)	Neurologic Injury Risk With ION (%)	Neurologic Injury Risk Without ION (%)	Sensitivity	Specificity	False Negative	False Positive
Bose *et al*[14]	2004	119	3 (2.5)	NR	NR	0.33	0.96	0.67	0.04
Bouchard *et al*[15]	1996	32	0 (0)	NR	NR	N/A	1.00	N/A	0.00
Gokaslan *et al*[16]	1997	16	0 (0)	NR	NR	N/A	1.00	N/A	0.00
Lee *et al*[17]	2006	Total: 1445 Corpectomy: 483	Total: 2 (0.01) Corpectomy: 2 (0.4)	NR	NR	1.00	0.82	0.00	0.18
Sebastian *et al*[18]	1997	Total: 210 Corpectomy: 80	Total: 0 (0) Corpectomy: 0 (0)	NR	NR	N/A	0.81	N/A	0.19
Smith *et al*[19]	2007	1039	1 (0.09)	1/577 (0.17)	0/462 (0)	0.00	0.99	1.00	0.01
Taunt *et al*[20]	2005	163	1 (0.6)	NR	NR	0.67	0.98	0.33	0.02
Xu *et al*[21]	2011	57	2 (3.5)	NR	NR	0.67	0.96	0.00	0.04
Cole *et al*[22]	2014	22768	28 (0.12)	5/5700 (0.09)	23/17068	N/A	N/A	N/A	N/A
Khan *et al*[23]	2006	508	12 (2.4)	NR	NR	0.77	1.00	0.23	0.00

Data for each study's individual sensitivity and specificity analysis.

The values represent the total sensitivity and specificity for all patients included in the study, the total value in "Number of Patients."

ION indicates intraoperative neuromonitoring; NR, not reported.

TABLE 5

Sensitivity and Specificity of Unimodal *Versus* Multimodal ION for ACSS

	Multimodal ION	Unimodal ION	P
Sensitivity (CI)	0.88 (0.04–1.0)	0.68 (0.39–0.88)	0.9495
Specificity (CI)	0.92 (0.81–0.96)	0.99 (0.97–1.0)	0.0218

CI indicates confidence interval; ION, intraoperative neuromonitoring.