Multimodality intraoperative neuromonitoring in extreme lateral interbody fusion

Berends, Hanneke I.; Journée, Henricus L.; Rácz, Ilona; van Loon, Jan; Härtl, Roger; Spruit, Maarten

Published in:
European Spine Journal

DOI:
10.1007/s00586-015-4182-9

Eur Spine J (2016) 25:1581–1586
DOI 10.1007/s00586-015-4182-9

ORIGINAL ARTICLE

Multimodality intraoperative neuromonitoring in extreme lateral interbody fusion. Transcranial electrical stimulation as indispensable rearview

Hanneke I. Berends[1] · Henricus L. Journée[2] · Ilona Rácz[1] · Jan van Loon[3] · Roger Härtl[4] · Maarten Spruit[3]

Received: 23 April 2015 / Revised: 5 August 2015 / Accepted: 6 August 2015 / Published online: 27 August 2015

Abstract
Purpose To optimize intraoperative neuromonitoring during extreme lateral interbody fusion (XLIF) by adding transcranial electrical stimulation with motor evoked potential (TESMEP) to previously described monitoring using spontaneous EMG (sEMG) and peripheral stimulation (triggered EMG: tEMG).
Methods Twenty-three patients with degenerative lumbar scoliosis had XLIF procedures and were monitored using sEMG, tEMG and TESMEP. Spontaneous and triggered muscle activity, and the MEP of 5 ipsilateral leg muscles, 2 contralateral leg muscles and 1 arm muscle were monitored.
Results During XLIF surgery decreased MEP amplitudes were measured in 9 patients and in 6 patients sEMG was documented. In 4 patients, both events were described. In 30 % of the cases ($n = 7$), the MEP amplitude decreased immediately after breaking of the table and even before skin incision. After reduction of the table break, the MEP amplitudes recovered to baseline. In two patients, the MEP amplitude deteriorated during distraction of the psoas with the retractor, while no events were reported using sEMG and tEMG. Repositioning of the retractor led to recovery of the MEP.
Conclusions Monitoring the complete nervous system during an XLIF procedure is found to be helpful since nerve roots, lumbar plexus as well as the intradural neural structures may be at risk. TESMEP has additional value to sEMG and tEMG during XLIF procedure: (1) it informed about otherwise unnoticed events, and (2) it confirmed and added information to events measured using sEMG.

Keywords Intraoperative neuromonitoring · XLIF · Transcranial electrical stimulation · TESMEP

Introduction

Extreme lateral interbody fusion (XLIF) is a less invasive technique for the treatment of degenerative lumbar spinal pathology and intervertebral disc injuries. During this transpsoas-technique, nerves of the lumbar plexus and exiting nerve roots are at risk. Appropriate intraoperative neuromonitoring (IONM) is necessary to minimize the risk of nerve injury. Many studies evaluating XLIF report sensory and motor complications despite the use of peripheral stimulation [triggered electromyography (tEMG)] and spontaneous EMG (sEMG) to monitor the motor system intraoperatively.

Studies presenting the early experience with the XLIF procedure report transient or persistent neurological complications including pain, numbness or muscle weakness [4, 5, 7, 10, 12, 13, 17, 18, 20, 21]. Although these studies describe the use of IONM, further specifications about the monitoring are mostly not mentioned.

Few studies describe the IONM procedures during XLIF and report the use of peripheral stimulation in combination

✉ Hanneke I. Berends
h.berends@maartenskliniek.nl

[1] Department of Anesthesiology, Sint Maartenskliniek, P.O. Box 9011, 6500 GM Nijmegen, The Netherlands

[2] Ortho-Spine Research Department, Sint Maartenskliniek, Nijmegen, The Netherlands

[3] Department of Orthopedics, Sint Maartenskliniek, Nijmegen, The Netherlands

[4] Department of Neurosurgery, Weill Cornell Brain and Spine Center, New York, USA

with spontaneous EMG (sEMG) [1, 6, 20, 22]. When using peripheral stimulation motor nerves can be mapped. Additionally, the monitoring of sensory nerves by peripheral stimulation is described by measuring the response of the antidromic nerve conduction [1]. The information of the stimulation is used for guidance to safely create a psoas passage for the surgeon and it can be decided in which direction the m. psoas can be safely retracted. Continuous EMG recording is used to detect spontaneous EMG activity (sEMG) from impacted nerves. The use of these modalities is found to decrease the occurrence of neurologic complications. However, the substantial amount of reported transient and permanent neurological complications underscores the need for improvement of the monitoring.

The present study examines the value of adding transcranial electrical stimulation and measuring the motor evoked potential (TESMEP) to sEMG and peripheral stimulation. In this way, the integrity of the whole motor system is monitored and the effect of potential damage of the nerve is assessed.

Methods

Twenty-three patients (mean age 58.6 ± 11.4, female 19, male 4) with degenerative lumbar scoliosis had XLIF procedures and were monitored using sEMG, tEMG and TESMEP. Fusion levels were L2–3 ($n = 12$), L3–4 ($n = 5$), L2–3–4 ($n = 5$) and L1-2-3-4 ($n = 1$).

Surgical procedure

Patients were in lateral decubitus position on the OR table and approaches were from the concave side. After breaking the table, the surgical levels were identified by C-arm and marked. After lumbotomy approach, the disc space was palpated and a K-wire was first introduced in the expected disc space. This was verified with C-arm. Then the psoas was dilated using 3 sequential dilators. The retractor (Ravine, K2 M, Virginia, USA) was introduced parallel to the psoas fibers, turned 90° and then the blades were distracted to expose the disc space. After C-arm verification, the blades were docked to the vertebral bodies. The disc was removed and disc height was restored with sequential blunt dilators. The final size determined the trial cage size. Finally, the cage (Aleuthian, K2 M, Virginia, USA) was filled with allograft bone and introduced in the disc space.

Spontaneous EMG

Pre-operatively and peroperatively, muscle activity of 8 muscles was continuously monitored using sEMG. Ipsilateral the m. abductor pollicis brevis (apb), m. vastus medialis (vm), m. rectus femoris (rf), m. vastus lateralis (vl), m. tibialis anterior (ta) and m. gastrocnemius (gas) were monitored. Contralateral activity of the rf and ta was monitored.

sEMG of the rf, vm and vl was measured using bipolar 12-mm subdermal needle electrodes pairs (Rochester Electro-Medical). sEMG of the other muscles was measured using 2 bipolar Ag/AgCl recording electrodes (3 M®), placed over the muscle belly. Pre-operatively sEMG was checked in order to detect pre-existing neuropathies. Muscle activity was defined as event when it persisted without direct surgical manipulation of the nerves. Additionally, any muscle activity was communicated to the surgeon to warn for approximation of the nerve or nerve root.

TESMEP

TESMEP was done using a (voltage) Neuro-Guard stimulator (JS-center, Bedum, The Netherlands). A bandpass filter was used with a high pass filter of 50 Hz, and a low pass filter of 2500 Hz (3 dB cut-off level). The positioning of the stimulation electrodes was done consistent to the standardized 10–20 system. Cz' was defined in the midline at 1 cm occipital from Cz. When stimulating at Cz'F, a monophasic pulse was used (Cz': anode, F: cathode). Two stimulating needle electrodes (anode: Rochester ref 016393, length 37 mm, diameter 26GA, uncoated) were inserted at Cz' in opposite direction towards both ears. The half of a cautery ground plate electrode over the forehead was used as F (cathode: 3 M ref 9160F). Additionally, needle electrodes were inserted at C3 and C4. The middle of the electrodes was placed at C3 and C4, 7 cm laterally to Cz on the line between Cz and the earlobes. When stimulating at C3C4, a biphasic pulse was used where each phase of a biphasic pulse was 100mcs (total duration of a biphasic pulse is 200mcs). Input impedances of these electrodes were checked and maintained below 460 Ω, which was essential to reduce its influence on the total electrode impedance [11].

After the patient was placed in lateral decubitus position, stimulation settings (voltage, interpulse interval, number of pulses per train and interburst interval) were optimized in order to receive stable supramaximal MEP amplitudes while minimizing the movement of the patient. After the baseline MEPs were received, measurements were started before breaking the table (Fig. 1).

Throughout the procedure, the amplitude, latency and morphology of the MEPs in the recorded muscles (see sEMG) were monitored. Decreased MEP amplitude to 50 % of baseline value was discussed with the surgeon. Additionally, any sudden decrease of the MEP amplitudes was discussed and documented.

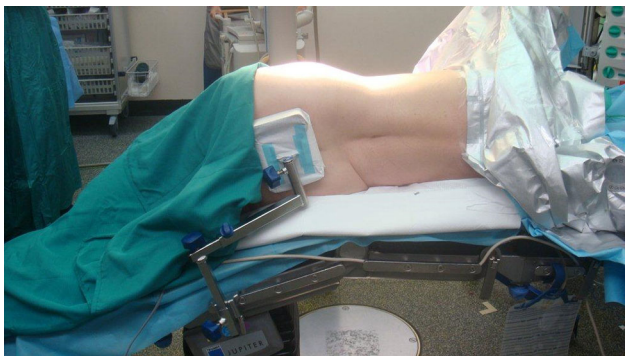

Fig. 1 Lateral decubitus position and breaking the table for XLIF procedure

Peripheral stimulation

Cathodal stimulation (Pulse width: 200 mcs, frequency: 3 Hz) was done using a monopolar concentric stimulation probe (Magstim Company). Anode was the half of a cautery end plate electrode, placed on the back of the patient. The triggered EMG (tEMG) was measured using the same channels as sEMG.

After traversing the psoas, tEMG was used to localize nerves in relation to the surgical area. When an evoked potential was seen in at least one of the EMG channels when using 20 mA, the threshold was determined in order to estimate the distance from stimulation point to the nerve. After docking the retractor to the vertebral bodies, the surgical area was stimulated to obtain a complete map of the anatomy of the nerves.

The following criteria were used in order to advice the surgeon [20]:

Threshold <5 mA: warning, too close to nerve (possible direct contact)

5 mA < threshold < 10 mA: caution

Threshold >10 mA: acceptable

In accordance to these criteria, the retractor was docked in its final position and the direction of the retraction of the psoas was determined.

When pre-existing compression of the nerve root was diagnosed, the warning criteria were adjusted.

Anaesthetic regime

All patients were sedated by total intravenous anaesthesia using propofol (maximum of 8 mg/kg/h), remifentanil (maximum of 0.5 μg/kg/min) and ketamine (2.5 μg/kg/min). No muscle relaxants were administered during the whole procedure. During induction of anaesthesia, a bolus of propofol and remifentanil was given. At minimally 30 min after induction, the optimal stimulation settings were defined. The non-invasive blood pressure was maintained at least at 60 mmHg. Normothermia was maintained using a warming blanket.

Clinical motor outcome

Pre- and 3–12 months post-operatively, the medical research council (MRC) is used to define maximum voluntary contraction of the finger flexors, m. biceps brachii, m. iliopsoas, m. rectus femoris, m. adductor femoris, m. tibialis anterior and m. gastrocnemius according to the American Spinal Injury Association (ASIA) score. Sensory function was assessed in the trunk area and the upper and lower extremities.

Analysis

Events measured using at least one of the three modalities (sEMG, tEMG, TESMEP) were documented. The measured event, expected causes, the reaction of the surgeon and the effect of the reaction on the event were linked, and related to the clinical outcome.

Results

In 19 patients an event was measured; in 13 patients a decreased MEP amplitude was measured using TESMEP, and in 10 patients sEMG events were documented. Table 1 summarizes the events, consecutive actions of the surgeon with the effects on the event, and the clinical motor outcome.

In 30 % of the cases ($n = 7$), the MEP amplitude of ipsilateral muscles decreased before the nerves were reached, or even before incision, but after breaking the table. After reduction of the table break, the MEP amplitudes recovered to baseline. In 5 out of 7 patients with decreased MEP amplitude related to breaking the table, motor strength was not affected 3 months post-operatively. In 2 patients the motor strength improved.

During the passage of the blunt dilator through the psoas, the TESMEP amplitudes decreased in one case, just after on-and-off sEMG was documented. The reason for the decrease and the spontaneous muscle activity at that very moment was not clear, and the surgeon continued the surgery. After retraction of the psoas the MEP amplitude recovered and the sEMG disappeared. The clinical outcome of this patient remained intact.

During positioning of the retractor in the psoas before docking events were measured in 5 patients. Ipsilateral

Table 1 Events measured using TESMEP and sEMG

Interpretation and likely cause of event (*n*)	TESMEP muscle	SEMG muscle, side	Both TESMEP and sEMG	Action surgeon	Result	Clinical motor outcome (MRC pre-op/post-op)
Pre-existing neurology (1)		$n = 1$ gas, ipsilat		–		Intact
Nerve traction after breaking table (7)	$n = 7$ vm/vl/rf			Reducing the break	MEP amplitude increased	Intact ($n = 3$) Same ($n = 2$) Better ($n = 2$) (MRC 4/5)
Blunt psoas dilation (1)			$n = 1$ vm ipsilat	Removal of the dilator	MEP amplitude increased sEMG response disappeared	Intact
Distraction of psoas with the retractor before docking (5)	$n = 2$ vm/vl/rf/ ta/gas	$n = 2$ vm/rf/ta/ gas, ipsilat	$n = 1$ TESMEP: vm/vl/ rf/ta/gas sEMG: vm/rf/ ta/gas, ipsilat	Release and repositioning of retractor	MEP amplitude increased sEMG response disappeared	TESMEP: Intact ($n = 2$) sEMG Better ($n = 1$) (MRC 3/5) Worse ($n = 1$) (MRC 4/3) TESMEP and sEMG Same ($n = 1$)
Discectomy (1)		$n = 1$ Vm, ipsilat		Distraction of disc space	sEMG disappeared	Intact
Distraction of the disc space (2)		$n = 2$ vm, vl, rf, contralat		Repositioning blunt dilator	sEMG disappeared	Worse ($n = 1$) (MRC 4/3) Better ($n = 1$) (MRC 5/5 (ipsilat), 4/5 contralat)
Trial cage insertion (2)			$n = 2$ (TES MEP: vm/rf/ vl, ipsilat sEMG: TA, gas, contralat	Smaller cage	MEP amplitude increase, sEMG disappeared	Same ($n = 1$) Worse ($n = 1$) (MRC 4/3)

n number of patients; muscles at which event is measured

TESMEP amplitudes decreased in 3 patients. In one of these patients spontaneous muscle activity was documented as well. In 2 other patients sEMG was measured without any effects on the MEP amplitude. All events were likely caused by compression or traction of the peripheral nerves because of retraction of the psoas and were resolved by repositioning of the retractor in the psoas. In 3 patients the motor strength post-operatively did not change, while it improved in one patient. Muscle strength was decreased in one patient directly after operation. However, 2 days post-operatively this patient mobilized without problems.

Contralateral sEMG and decreased MEP amplitudes were measured in relation to discectomy ($n = 1$), subsequent dilation of the disc space with blunt dilators ($n = 2$) and after trial cage introduction ($n = 2$). During surgery, the dilators were used in increasing size. When spontaneous muscle activity or decreased TESMEP amplitude was measured after placement of a larger diameter dilator, the surgeon decided to use a smaller cage to reduce traction on the intradural neural structures and nerve roots.

Peripheral stimulation

In 19 patients peripheral stimulation resulted in an MEP in at least one of the ipsilateral muscles measured. In 2 patients (surgical levels L2-3 and L2-3-4) no EMG reaction at all was observed after peripheral stimulation. Technical failure was excluded by positive muscle contraction during direct psoas muscle stimulation in the surgical site. Threshold of the MEPs was in the range of 1.0 to 15.0 mA.

Sensibility

At least 6 months after the surgery, 8 patients suffered from hypo- or hypersensibility ipsilateral or contralateral to the side of the surgery. Reported problems were as follows:

- Hyposensibility of
  - ipsilateral groin ($n = 2$),
  - ipsilateral groin ($n = 2$),
  - lateral aspect lower leg ($n = 1$),
  - contralateral upper leg ($n = 1$),
  - ipsilateral groin and thigh ($n = 1$),
  - ipsilateral lateral aspect leg ($n = 1$);
- Disturbed vital sensibility of ipsilateral leg ($n = 1$); and
- Hypersensibility of both legs ($n = 1$).

Discussion

Monitoring the complete motoric nervous system during an XLIF procedure is found to be helpful since nerve roots, lumbar plexus as well as the intradural neural structures may be at risk during surgery. Previous studies described the single use of sEMG and tEMG for IONM during XLIF surgery [3, 5, 9, 12, 13, 16, 20, 22]. In the present study, the additional value of TESMEP to sEMG and tEMG was found to be twofold: (1) it informed about otherwise unnoticed events, and (2) it confirmed and added information to events measured using sEMG.

In the reported patient population, the TESMEP was found to be of value as breaking of the OR table frequently resulted in decreased MEP amplitudes. This was likely attributed to traction on the neural tissue or possibly to decreased perfusion due to vascular traction. Without reducing the table break, the peripheral nerves might have been damaged and the risk of further damage to the nerves by the surgery might have occurred. Additionally, TESMEP was found to be helpful in monitoring the stress of the motor system caused by retraction of the psoas and after introduction of the trial cage.

Warning criteria of MEP amplitudes are not easily defined as damage to each of the neural tissues may have different impact on the TESMEP amplitudes, and therefore, different warning criteria should be used [2, 5, 8, 14]. Damage to the peripheral nerve might, for example, result in a higher amplitude loss of one muscle in particular compared to that after damage to the nerve root or lumbar plexus. Disturbed innervation of other muscles might be an additional problem.

Individual variability of the relative contribution of root-level motor input to various muscle groups exists [19]. Additionally, the length of retraction time or compression time of a nerve is found to influence the tEMG thresholds and possibly also the TESMEP amplitude [23]. This has to be taken into account during interpretation of changes of the TESMEP amplitude. When the decreased amplitude of the TESMEP is found before incision, time of the compression of the nerve will be long and it is advised to use strict alarm criteria. In our study, we defined an event as 50 % TESMEP amplitude loss of at least 1 muscle. Furthermore, any obvious or sudden TESMEP amplitude loss was communicated to the surgeon and the subsequent action of the surgeon always improved TESMEP amplitudes. This indicates real events despite the fact that the ultimate clinical effect may be unclear.

sEMG is very useful during XLIF surgery since it gives continuous information without disturbing the surgery. In the current study, spontaneous muscle activity was continuously measured to control the damage of the nerve roots while positioning the retractor and determining the cage size. Additionally, the extra TESMEP monitoring provides valuable information for better interpretation of measurements.

According to the documented events, which were measured in both ipsilateral and contralateral muscles, it is recommended to measure at least the quadriceps and tibial muscles bilaterally. Contralaterally measured events might indicate irritation by traction on nerve roots caused, for example by a large cage size or by malpositioning of the cage [15]. It is recommended also to use at least 1 muscle above the levels at risk as a control. When deciding which muscles should be monitored, one has to consider the surgical level and pre-existing pathology.

Monitoring of the sensory nerve system during the XLIF procedure is challenging. Although a low and wide amplitude MEP can be induced by antidromic conduction using the peripheral stimulation [1], the intermingling of the nerve roots in the lumbar plexus makes the innervation area large and overlapping. The number of dermatomes at risk is large, and obtaining reliable signals is likely too time-consuming to include in the monitoring protocol.

In conclusion, our study demonstrates that during XLIF surgery, the motor nerve system can be reliably monitored using multimodality IONM, where TESMEP is of complementary value to the routine use of tEMG and sEMG. The extra events noted were related to breaking of the table prior to incision, positioning of the retractor through the psoas muscle and introduction of the trial cage. We therefore recommend multimodality IONM including TESMEP in XLIF surgery.

Compliance with the ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Funding AOSpine TK system funded the study. We thank them for providing the financial support.

References

1. Bendersky M, Solá C, Muntadas J, Gruenberg M, Calligaris S, Mereles M, Valacco M, Bassani J, Nicolás M (2015) Monitoring lumbar plexus integrity in extreme lateral transpsoas approaches to the lumbar spine: a new protocol with anatomical bases. Eur Spin J 24:1051–1057. doi:10.1007/s00586-015-3801-9
2. Benglis DM, Vanni S, Levi AD (2009) An anatomical study of the lumbosacral plexus as related to the minimally invasive transpsoas approach to the lumbar spine. J Neurosurg Spine 10(2):139–144. doi:10.3171/2008.10.SPI08479
3. Berjano P, Lamartina C (2013) Far lateral approaches (XLIF) in adult scoliosis. Eur Spine J 22(Suppl 2):S242–S253. doi:10.1007/s00586-012-2426-5
4. Cahill KS, Martinez JL, Wang MY, Vanni S, Levi AD (2012) Motor nerve injuries following the minimally invasive lateral transpoas approach. J Neurosurg Spine 17(3):227–231. doi:10.3171/2012.5.SPINE1288
5. Dakwar E, Cardona RF, Smith DA, Uribe JS (2010) Early outcomes and safety of the minimally invasive, lateral retroperitoneal transpsoas approach for adult degenerative scoliosis. Neurosurg Focus 28(3):E8. doi:10.3171/2010.1
6. Gazzeri R, Faiola A, Neroni M, Fiore C, Callovini G, Pischedda M, Galarza M (2013) Safety of intraoperative electrophysiological monitoring (TES and EMG) for spinal and cranial lesions. Surg Technol Int 23:296–306
7. Grimm BD, Leas DP, Poletti SC, Johnson DR 2nd (2014) Postoperative complications within the first year after extreme lateral interbody fusion: experience of the first 108 patients. J Spinal Disord Tech. doi:10.1097/BSD.0000000000000121
8. Guérin P, Obeid I, Bourghli A, Masquefa T, Luc S, Gille O, Pointillart V, Vital J-M (2012) The lumbosacral plexus: anatomic consideration for minimally invasive retroperitoneal transpsoas approach. Surg Radiol Anat 34:151–157. doi:10.1007/s00276-011-0881-z
9. Houten JK, Alexandre LC, Nasser R, Wollowick AL (2011) Nerve infury during the transpsoas approach for lumbar fusion. Report of 2 cases. J Neurosurg Spine 15:280–284. doi:10.3171/2011.4.SPINE1127
10. Hrabalek L, Adamus M, Gryga A, Wanek T, Tucek P (2014) A comparison of complication rate between anterior and lateral approaches to the lumbar spine. Biomed Pap Med Fac Univ Palacky Olomouc Czech Repub 158(1):127–132. doi:10.5507/pb.2012.079
11. Journée HL, Polak HE, de Kleuver M (2004) Influence of electrode impedance on threshold voltage for transcranial electrical stimulation in motor evoked potential monitoring. Med Biol Eng Comput 42(4):557–561
12. Knight RQ, Schwaegler P, Hanscom D, Roh J (2009) Direct lateral lumbar interbody fusion for degenerative conditions. Early complication Profile. J Spinal Disord Tech 22:34–37. doi:10.1097/BSD.0b013e3181679b8a
13. Malham GM, Ellis NJ, Parker RM, Seex KA (2012) Clinical outcome and fusion rates after the first 20 extreme lateral interbody fusions. Sci World J. doi:10.1100/2012/246989 **(246989)**
14. Moro T, Kiluchi S, Konno S, Yaginuma H (2003) An anatomic study of the lumbar plexus with respect to retroperitoneal endoscopic surgery. Spine 28:423–428
15. Papanastassiou ID, Eleraky M, Vrionis FD (2011) Contralateral femoral nerve compression: an unrecognized complication after extreme lateral interbody fusion (XLIF). J Clin Neurosci 18(1):149–151. doi:10.1016/j.jocn.2010.07.109
16. Park DK, Lee MJ, Lin EL, Singh K, An HS, Philips FM (2010) The relationship of intrapsoas nerves during a transpsoas approach to the lumbar spine. Anatomic study. J Spinal Disord Tech 23:223–228. doi:10.1097/BSD.0b013e3181a9d540
17. Rodgers WB, Gerber EJ, Patterson J (2011) Intraoperative and early postoperative complications in extreme lateral interbody fusion. Spine 36(1):26–32. doi:10.10907/BRS.0b013e3181e1040a
18. Rodgers WB, Lehmen JA, Gerber EJ, Rodgers JA (2012) Grade 2 spondylolisthesis at L4-5 treated by XLIF: safety and midterm results in the "worst case scenario". Sci World J. doi:10.1100/2012/356712 **(356712)**
19. Schirmer CM, Shils JL, Arle JE, Cosgrove GR, Dempsey PK, Tarlov E, Kim S, Martin CJ, Feltz C, Moul M, Magge S (2011) Heuristic map of myotomal innervation in humans using direct intraoperative nerve root stimulation. J Neurosurg Spine 15:64–70. doi:10.3171/2011.2.SPINE1068
20. Tohmeh AG, Rodgers WB, Peterson MD (2011) Dynamically evoked, discrete-threshold electromyography in the extreme lateral interbody fusion approach. J Neurosurg Spine 14:31–37. doi:10.3171/2010.9
21. Tormenti MJ, Maserati MB, Bonfield CM, Okonkwo DO, Kanter AS (2010) Complications and radiographic correction in adult scoliosis following combined transpoas extreme lateral interbody fusion and posterior pedicle screw instrumentation. Neurosurg Focus 28(3):E7. doi:10.3171/2010.1
22. Uribe JS, Vale FL, Dakwar E (2010) Electromyographic monitoring and its anatomical implications in minimally invasive spine surgery. Spine 35(16 Suppl):S368–S374. doi:10.1097/BRS.0b013e3182027976
23. Uribe JS, Isaacs RE, Youssef JA, Khajavi K, Balzer JR, Kanter AS, Küelling FA, Peterson MD (2015) Eur Spine J 24(suppl 3):S379–S385. doi:10.1007/s00586-015-3871-8