VOLUME 22, ISSUE 2, P296-304, FEBRUARY 01, 2022

The SPINE JOURNAL

The Spine Journal 000 (2021) 1−9

Clinical study

Femoral nerve neuromonitoring for lateral lumbar interbody fusion surgery

Justin W. Silverstein, DHSc[a,h,r,*], Jon Block, DC[b], Michael L. Smith, MD[c,h], David A. Bomback, MD[d,p], Scott Sanderson, MD[e,p], Justin Paul, MD[f,p], Hieu Ball, MD[g], Jason A. Ellis, MD[h], Matthew Goldstein, MD[i,q], David L. Kramer, MD[d,p], Grigoriy Arutyunyan, MD[c,h], Joshua Marcus, MD[e,p], Sara Mermelstein, BS[j], Paul Slosar, MD[k], Noel Goldthwaite, MD[k], Sun Ik Lee, MD[l], James Reynolds, MD[k], Margaret Riordan, MD[m], Nick Pirnia, MD[m], Sandeep Kunwar, MD[n], Saqib Hasan, MD[g], Bruce Bizzini, CNIM[b], Sarita Gupta, MD[b], Dorothy Porter, BS[a], Laurence E. Mermelstein, MD[o,r]

[a] *Neuro Protective Solutions, New York, NY 11788, USA*
[b] *ION Intraoperative Neurophysiology, Orinda, CA, USA*
[c] *Rothman Orthopedic Institute, New York, NY, USA*
[d] *Connecticut Neck and Back Specialists, Danbury, CT, USA*
[e] *Elite Brain and Spine of Connecticut, Danbury CT, USA*
[f] *OrthoConnecticut, Danbury CT, USA*
[g] *San Ramon Regional Medical Center, San Ramon, CA, USA*
[h] *Northwell Health Lenox Hill Hospital, New York, NY, USA*
[i] *Orthopedic Associates of Manhasset, Great Neck, NY, USA*
[j] *New York Institute of Technology College of Osteopathic Medicine, Old Westbury, NY, USA*
[k] *Seton Medical Center, Daly City, CA, USA*
[l] *Highland Hospital, Oakland, CA, USA*
[m] *Alameda Hospital, Alameda, CA, USA*
[n] *Washington Hospital, Freemont, CA, USA*
[o] *Long Island Spine Specialists, Long Island, NY, USA*
[p] *Nuvance Health, Danbury, CT, USA*
[q] *St. Francis Hospital, Roslyn, NY, USA*
[r] *Northwell Health Huntington Hospital, Huntington, NY, USA*

Received 1 May 2021; revised 26 June 2021; accepted 26 July 2021

Abstract

BACKGROUND CONTEXT: The transpsoas lateral lumbar interbody fusion (LLIF) technique is an effective alternative to traditional anterior and posterior approaches to the lumbar spine; however, nerve injuries are the most reported postoperative complication. Commonly used strategies to avoid nerve injury (eg, limiting retraction duration) have not been effective in detecting or preventing femoral nerve injuries.

PURPOSE: To evaluate the efficacy of emerging intraoperative femoral nerve monitoring techniques and the importance of employing prompt surgical countermeasures when degraded femoral nerve function is detected.

.FDA device/drug status: Not applicable

Author disclosures: ***JWS:*** Nothing to disclose. ***JB:*** Nothing to disclose. ***MLS:*** Nothing to disclose. ***DAB:*** Nothing to disclose. ***SS:*** Nothing to disclose. ***JP:*** Nothing to disclose. ***HB:*** Nothing to disclose. ***JAE:*** Nothing to disclose. ***MG:*** Nothing to disclose. ***DLK:*** Nothing to disclose. ***GA:*** Nothing to disclose. ***JM:*** Nothing to disclose. ***SM:*** Nothing to disclose. ***PS:*** Nothing to disclose. ***NG:*** Nothing to disclose. ***SIL:*** Nothing to disclose. ***JR:*** Nothing to disclose. ***MR:*** Nothing to disclose. ***NP:*** Nothing to disclose. ***SK:*** Nothing to disclose. ***SH:*** Nothing to disclose. ***BB:*** Nothing to disclose. ***SG:*** Nothing to disclose. ***DP:*** Nothing to disclose. ***LEM:*** Nothing to disclose.

*Corresponding author. Neuro Protective Solutions, 140 Adams Ave, Ste B13, Hauppauge, NY 11788, USA. Tel.: +1 5169020057

E-mail address: wiredneuro@gmail.com (J.W. Silverstein).

https://doi.org/10.1016/j.spinee.2021.07.017
1529-9430/

STUDY DESIGN/SETTING: We present the results from a retrospective analysis of a multi-center study conducted over the course of 3 years.

PATIENT SAMPLE: One hundred and seventy-two lateral lumbar interbody fusion procedures were reviewed.

OUTCOME MEASURES: Intraoperative femoral nerve monitoring data was correlated to immediate postoperative neurologic examinations.

METHODS: Femoral nerve evoked potentials (FNEP) including saphenous nerve somatosensory evoked potentials (snSSEP) and motor evoked potentials with quadriceps recordings were used to detect evidence of degraded femoral nerve function during the time of surgical retraction.

RESULTS: In 89% (n=153) of the surgeries, there were no surgeon alerts as the FNEP response amplitudes remained relatively unchanged throughout the surgery (negative group). The positive group included 11% of the cases (n=19) where the surgeon was alerted to a deterioration of the FNEP amplitudes during surgical retraction. Prompt surgical countermeasures to an FNEP alert included loosening, adjusting, or removing surgical retraction, and/or requesting an increase in blood pressure from the anesthesiologist. All the cases where prompt surgical countermeasures were employed resulted in recovery of the degraded FNEP amplitudes and no postoperative femoral nerve injuries. In two cases, the surgeons were given verbal alerts of degraded FNEPs but did not employ prompt surgical countermeasures. In both cases, the degraded FNEP amplitudes did not recover by the time of surgical closure, and both patients exhibited postoperative signs of sensorimotor femoral nerve injury including anterior thigh numbness and weakened knee extension.

CONCLUSIONS: Multimodal femoral nerve monitoring can provide surgeons with a timely alert to hyperacute femoral nerve conduction failure, enabling prompt surgical countermeasures to be employed that can mitigate or avoid femoral nerve injury. Our data also suggests that the common strategy of limiting retraction duration may not be effective in preventing iatrogenic femoral nerve injuries.

Keywords: Saphenous nerve; Motor evoked potentials; Somatosensory evoked potentials; Femoral nerve; Lumbar lateral interbody fusion; Quadriceps; Nerve injury.

Abbreviations: LLIF, lateral lumbar interbody fusion; SSEPs, somatosensory evoked potentials; MEPs, motor evoked potentials; FNEPs, femoral nerve evoked potentials (snSSEP & MEPq); snSSEP, saphenous nerve somatosensory evoked potentials; MEPq, transcranial motor evoked potentials with quadriceps recordings; sEMG, spontaneous (free running) electromyography recordings; tEMG, triggered electromyography for nerve localization (mapping); PTN, posterior tibial nerve; ptnSSEP, posterior tibial nerve somatosensory evoked potentials; TIVA, total intravenous anesthesia

Introduction

The transpsoas lateral lumbar interbody fusion (LLIF) technique is an effective alternative to traditional anterior and posterior approaches to the lumbar spine [1].The advantages of the LLIF are well documented, however injuries to the lumbar plexus are the most reported postoperative complication [2]. Injury to the neural elements of the lumbar plexus can range from low grade transient neuropraxia to high grade injuries with axonal damage and the potential for permanent disability. A high-grade femoral nerve injury is the most feared neurologic complication, with the suspected highest risk at the L4−L5 level where the variable path of the femoral nerve can run directly across the disc space [3]. Most nerve injuries associated with LLIF procedures should be classified as plexopathies, which have different prognostic, and management implications compared with radicular injuries that are associated with traditional posterior approaches to the lumbar spine where the nerve roots are most at risk [2]. This important anatomical distinction also applies to neuromonitoring protocols for the lumbar plexus and/or femoral nerve, which must be approached differently than those used to monitor the function of the spinal cord and nerve roots [4].

This publication provides an overview of emerging intraoperative femoral nerve monitoring techniques and a review of our results from a multi-center study conducted over the course of 3 years.

Materials and methods

Institutional review board approval was granted for this study and intraoperative monitoring data from 172 LLIF procedures (103 females and 69 males with a mean age of 66 years) consisting of 278 surgical levels (L1−L2=9; L2−L3=66, L3−L4=118, L4−L5=85) were prospectively collected and retrospectively analyzed. Fellowship trained orthopedic spine and neurologic surgeons performed all the LLIF procedures. Multimodal neurophysiological monitoring using somatosensory evoked potentials (SSEP), electromyography (EMG), and motor evoked potentials (MEPs) was performed by board certified surgical neurophysiologists with specialized training in femoral nerve monitoring techniques. The neuromonitoring data was reviewed and correlated to immediate postoperative examination findings.

Each patient was positioned in a lateral decubitus position and the transpsoas approach was performed as described by multiple authors [1,5−6] To establish a safe surgical corridor to the disc space, common nerve mapping techniques using triggered electromyography (tEMG) were employed to detect motor nerve fibers in proximity to the tip of each of the surgical instruments (eg, dilators, retractor blade, hand-held probe), which are fitted with a monopolar stimulating electrode. Once a safe surgical corridor was established and the surgical retractors were deployed, the neurophysiologist switched their focus from nerve mapping to femoral nerve monitoring for the purpose of detecting any evidence of degraded femoral nerve function during surgical retraction.

Intraoperative neurophysiological monitoring methods

Baseline Femoral Nerve Evoked Potentials (FNEPs) including both saphenous nerve SSEPs (snSSEPs) and motor evoked potentials with quadriceps recordings (MEPqs) were acquired before skin incision. Baselines of control recordings (non−femoral nerve SSEPs and MEPs) were also acquired for comparison. The surgeon was advised of the quality of the baseline data as a measure of how effective the femoral nerve monitoring would be for that particular case, as the quality of FNEP data can be highly variable between patients and under different anesthetic conditions.

Alert criterion was defined as an isolated degradation in amplitude of the surgical side snSSEP and/or MEPq responses while the amplitudes from all other non−femoral nerve innervated evoked potential recordings (control recordings) remained unchanged. Alerts were also provided if any abnormal spontaneous electromyography (sEMG) activity was observed, with particular attention on the lumbar plexus innervated muscles.

Femoral nerve monitoring using femoral nerve evoked potentials (FNEPs)

FNEPs including both snSSEPs and MEPqs, were acquired near the time of incision to establish baseline amplitudes. The neurophysiologist provided the surgeon with a verbal report using three basic categories that subjectively describe the quality of the acquired snSSEP and MEPq baseline recordings:

- Good- repeatable responses with ample, consistent amplitudes, and stable waveform morphologies
- Poor- inconsistent, variable, or low amplitude responses
- Unobtainable- no viable, repeatable recordings can be acquired

Results

We were able to confidently monitor the sensory function of the femoral nerve by obtaining good quality snSSEP responses at baseline in 84% of the cases (144 patients) using electrical activation of the saphenous nerve at the distal medial thigh and recording the resultant cortical sensory evoked potentials with subdermal scalp electrodes. In 16% of the cases (28 patients), baseline snSSEP recordings were poor or unobtainable. We were able to confidently monitor the motor function of the femoral nerve with good quality baseline MEPq responses in 57% of the cases (98 patients) using transcranial electrical stimulation with at least two quadriceps muscle recording channels (ie, vastus medialis and vastus lateralis). Poor quality MEPq baselines were acquired in 30% of cases (52 patients) and there were 12% of cases (20 patients) where baselines were unobtainable. One percent (two patients) were omitted due to contraindications for MEP monitoring.

Detecting degraded FNEPs during surgical retraction

Our case series consisted of 172 surgeries with 278 surgical levels. In 89% (n=153) of the surgeries (248 surgical levels), there were no surgeon alerts as the FNEP response amplitudes remained relatively unchanged throughout surgical retraction and until closure (Negative group). The positive group included 11% of the cases (n=19) where the surgeon was alerted to an isolated deterioration of the surgical-side FNEP amplitudes during surgical retraction (Table 1). Degraded FNEPs were not observed in the one case in our series that was performed at the L1−L2 level. At the L2−L3 level, we detected FNEP amplitude degradation in three cases. We detected a greater number of degraded FNEPs at the L3−L4 level (nine cases) compared with the L4−L5 level (seven cases). In 17 of the 19 cases where degraded FNEPs were detected, the surgeons employed prompt surgical countermeasures that included loosening, adjusting, or removing surgical retraction, and/or requesting an increase in blood pressure from the anesthesiologist. All 17 of these cases where prompt surgical countermeasures were employed resulted in recovery of the degraded FNEP amplitudes and no postoperative femoral nerve injuries. In two cases, the surgeons were given verbal alerts of degraded FNEPs but did not employ prompt surgical countermeasures. In both cases, the degraded FNEP amplitudes did not recover by the time of surgical closure, and both patients exhibited postoperative signs of sensorimotor femoral nerve injury including anterior thigh numbness and weakened knee extension.

Our study revealed an 11% alert rate and a 1% rate of femoral nerve injury that only occurred in the two cases where no prompt surgical countermeasures were employed following an alert of degraded FNEPs.

Spontaneous electromyography (sEMG)

Continuous sEMG recordings were closely observed during surgical retraction to detect any evidence of abnormal spontaneous muscle activity (ie, neurotonic discharges) that might be considered suggestive of nerve stretch, compression or irritation. Continuous sEMG recordings of

Table 1
Positive group – summary of results for the 19 patients where degraded FNEP data was observed along with postoperative outcomes.

Case	Sex	Procedure	Level of FNEP degradation	snSSEP	MEPq	Retraction time to FNEP conduction failure in min	Surgical countermeasure	FNEP recovery by closure	Postop exam
1	F	L2–L5 LLIF	L4–L5	Loss	Unobtainable	40	Increase BP and retractor removal	Yes	Neuro Intact
2	M	L2–L4 LLIF	L2–L3	Unobtainable	Loss	1	Retractor removal	Yes	Neuro intact
3	M	L3–L5 LLIF	L4–L5	Unobtainable	Loss	35	Retractor Removal	Yes	Neuro intact
4	M	L3–L4 LLIF	L3–L4	Loss	Loss	12	Retractor Removal	Yes	Neuro Intact
5	M	L3–L4 LLIF	L3–L4	Unobtainable	Loss	20	Retractor Removal	Yes	Neuro Intact
6	F	L3–L4 LLIF	L3–L4	Degraded Amplitude	Loss	6	Retraction removal	Yes	Neuro Intact
7	F	L2–L5 LLIF	L2–L3	Unreliable	Loss	18	Retractor removal	Yes	Neuro Intact
8	F	L4–L5 LLIF	L4–L5	Loss	Loss	20	No Intervention	No	Femoral nerve sensorimotor deficit
9	F	L4–L5 LLIF	L4–L5	Unobtainable	Loss	23	Retractor Removal	Yes	Neuro Intact
10	F	L4–L5 LLIF	L4–L5	Loss	Loss	26	Hastened Procedure	Yes	Neuro Intact
11	M	L3–L4 LLIF	L3–L4	Loss	Unobtainable	33	Retractor removal	Yes	Neuro Intact
12	F	L3–L4 LLIF	L3–L4	Unobtainable	Immediate Loss	1	Retractor removal	Yes	Neuro Intact
13	F	L4–L5 LLIF	L4–L5	Loss	Unobtainable	21	Hastened Procedure	Yes	Neuro Intact
14	F	L4–L5 LLIF	L4–L5	Loss	Loss	5	Retractor removal	Yes	Neuro Intact
15	F	L3–L4 LLIF	L3–L4	Loss	Loss	30	Retractor Removal	Yes	Neuro Intact
16	M	L3–L4 LLIF	L3–L4	Loss	Loss	14	Retractor removal	Yes	Neuro Intact
17	F	L3–L4 LLIF	L3–L4	Unobtainable	Loss	26	No Intervention	No	Femoral nerve sensorimotor deficits
18	M	L1–L3 LLIF	L2–L3	Loss	Loss	7	Retractor removal	Yes	Neuro Intact
19	M	L3–L4 LLIF	L3–L4	Loss	Loss	24	Retractor loosening	Yes	Neuro Intact

Table 2
Muscles used for sEMG, tEMG, and MEP recordings.

	Muscle recording channel	Root/Plexus/Peripheral nerve
Lumbar plexus muscle recordings	Abdominals	T12, L1 / Lumbar Plexus / Subcostal nerve (T12), Illiohypogastric Nerve (L1) & Ilioinguinal Nerve (L1)
	Adductors	L2, L3, L4 / Lumbar Plexus / Obturator nerve
	Quadriceps- at least two muscle recording channels (ie, vastus medialis & vastus lateralis)	L2, L3, L4 / Lumbar Plexus / Femoral nerve
Sacral plexus (control recordings)	Tibialis Anterior	L4, L5 Sacral Plexus / Sciatic/Peroneal nerve
	Gastrocnemius	S1−S2/ Sacral Plexus / Sciatic / Posterior Tibial Nerve
	Abductor Hallucis	S1, S2, S3 / Sacral Plexus / Sciatic / Posterior Tibial Nerve

multiple muscles (Table 2) included mainly muscles innervated by the lumbar plexus with additional control recordings of muscles innervated by the sciatic nerve which is not typically at risk in LLIFs. In our study, sEMG recordings were not found to be useful as an alert of nerve compromise, and no significant abnormal sEMG activity was observed in any of the patients including the positive group where degraded surgical-side FNEPs were observed.

Surgical retraction time

The mean total surgical retraction duration was 29 minutes per surgical level. The mean retraction duration of the negative group was 29 minutes. For the positive group, the average time from the onset of retraction until FNEP degradation was 19 minutes, significantly less (p=.001) than the average total retraction time of the negative group.

Discussion

A recent systematic review of 63 articles (6,819 patients) focusing on LLIF complications report transient neurologic injuries at a rate of 36.07% and persistent neurologic complications at a rate of 3.9% [12]. The most feared neurologic complication is a high-grade femoral nerve injury which can be permanently debilitating [2,5−15]. An accurate incidence of femoral nerve injuries has been somewhat elusive as many authors believe that femoral nerve injuries have been underreported and inconsistently categorized in the literature. Clear guidelines for classifying lumbar plexus injuries following LLIF procedures were published by Ahmadian *et al.* (2013) [2].

Most authors agree that excessive and/or prolonged surgical retraction can cause stretch or compression of the femoral nerve or its related vasculature [3,14−18]. Surgical retraction can result in occlusion of the tissue blood supply resulting in ischemic damage [19]. The theory for femoral nerve monitoring in LLIFs is based on how peripheral nerve function responds to applied mechanical forces over time. Various animal studies have demonstrated how mechanical forces applied to peripheral nerves can result in reversible conduction failure that can fully resolve if the forces are removed within a short period of time and how prolonged and/or excessive forces can lead to permanent nerve dysfunction [20−25].

The primary goal of femoral nerve monitoring is to detect hyperacute femoral nerve conduction failure so that the surgeon may employ surgical countermeasures to reduce the strain on the femoral nerve to during the critical time period where the conduction failure is reversible [4,26−36]. In our study, prompt removal of surgical retraction following detection of degraded FNEP amplitudes always resulted in FNEP amplitude recovery. Additionally, increasing the blood pressure following a degradation in FNEP amplitudes may assist in nerve reperfusion from retraction induced ischemia [19].

Our investigators highly recommend utilizing both FNEP techniques which are complimentary, providing the surgeon with a continuous functional assessment of both the sensory and motor components of the femoral nerve. Utilizing both sensory and motor recordings is even more important in cases where the data from one of the modalities is poor or unobtainable, which is not uncommon.

The results of our study suggest that multimodal femoral nerve monitoring utilizing FNEPs is highly effective for detecting hyperacute femoral nerve conduction failure during surgical retraction in LLIF procedures. Our study revealed a high predictive value with a 100% correlation between well-preserved FNEP amplitudes at the time of surgical closure resulting in good postoperative outcomes (Fig. 1). Poor outcomes were also accurately predicted in the two patients (1%) where degraded FNEP recordings did not recover by the time of surgical closure (Fig. 2).

Contrary to expectations, we detected a slightly greater number of degraded FNEPs at the L3−L4 level (nine cases) compared with the L4−L5 level (seven cases). Cadaveric anatomical investigations describe considerable anatomical variability in the formation and branching patterns of the lumbar plexus including prefixed and postfixed lumbar plexuses [37−40]. Our study results suggest that surgeons and neurophysiologists should be attentive to the FNEPs at the levels rostral to the L4−L5 level which has traditionally been suspected to be the level of highest risk.

Surgeons should appreciate the technical obstacles, pitfalls, limitations, and strengths of femoral nerve monitoring to use the information most effectively for surgical decision

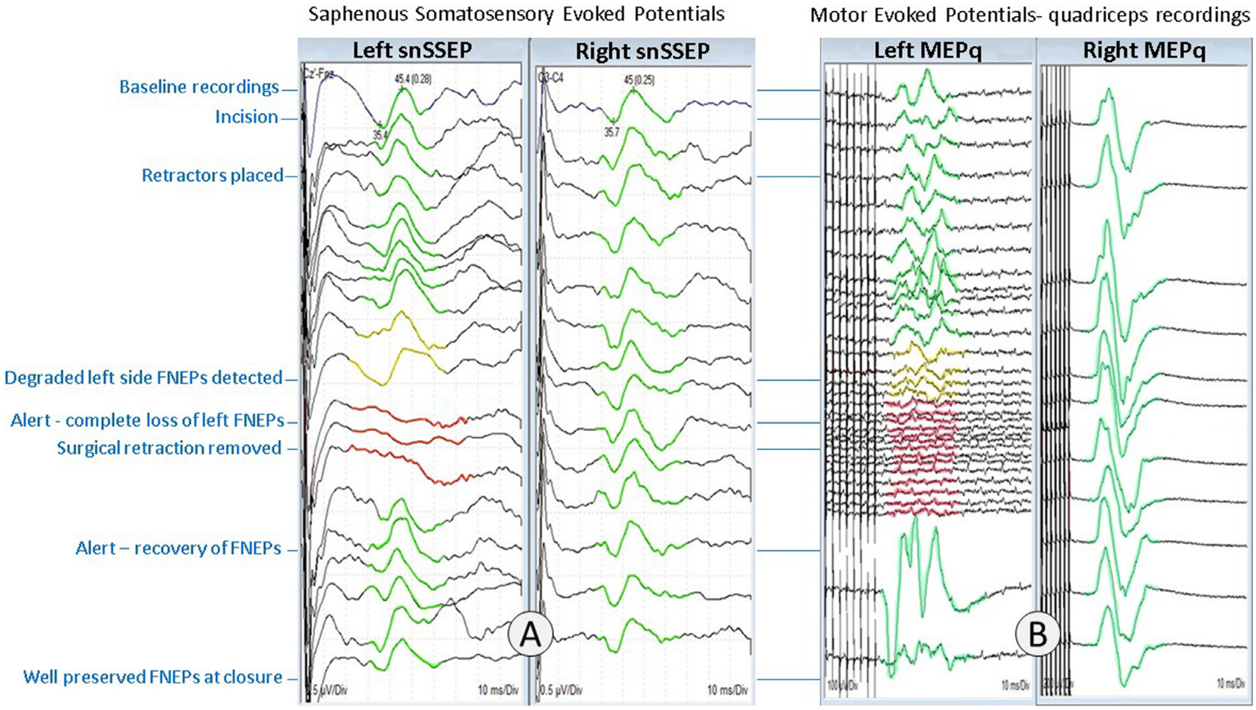

Fig. 1. Case Example 1- Hyperacute femoral nerve conduction failure during surgical retraction detected and corrected. A "waterfall" view shows the FNEP data chronologically from the beginning of the L4−L5 LLIF procedure (top) until surgical closure (bottom). This was the first documented case where hyperacute femoral nerve conduction failure was detected concurrently in both the surgical side snSSEPs and MEPq while all control evoked potential recordings remained unchanged. (A) The baseline snSSEP amplitude (green) on the left (surgical side) begins to degrade (yellow) during surgical retraction until the signal is completely lost (red). Following release of the surgical retraction, the degraded signals quickly recover to near baseline amplitudes (green). In contrast, the right (non−surgical side) snSSEP response amplitudes remained unchanged throughout the procedure. (B) The left side motor evoked potential quadriceps recordings (MEPq) confirmed failing femoral nerve function with degraded response amplitudes (yellow) followed by a complete loss of the response (red), while the right sided responses remained unchanged. Like the degraded left snSSEP responses, the degraded left MEPq responses also rapidly recovered to near baseline amplitudes following prompt removal of the surgical retraction. The left sensory and motor femoral nerve evoked potential responses remained within normal limits at the time of surgical closure and this patient did not experience any postoperative neurologic deficits (Color version of the figure is available online.).

making. Widespread adoption of femoral neuromonitoring techniques may be slow due to technical challenges and the limited number of qualified neurophysiologists with the ability to successfully acquire useful data and provide the surgeon with an appropriate interpretation. The quality of the FNEP data can vary significantly between patients and can be influenced by several factors including anesthetic levels, technical factors, physiological factors, and comorbidities. At the time of incision, the neurophysiologist should provide a detailed verbal report describing the quality of the baseline FNEPs to the surgeon. The report should include qualitative descriptions of both the snSSEPs and MEPq data (ie, good, poor, absent) that will provide the surgeon with a level of confidence in their ability to monitor femoral nerve function for that particular patient. The quality of the acquired FNEP data is different for each case, and effective communication between the surgeon, neurophysiologist and anesthesiologist is essential. If the baseline snSSEPs are poor, the surgeon must solely rely on the MEPq data to assess femoral nerve function, and thus MEPq data must be acquired more often throughout the procedure. The snSSEP data can be acquired continuously throughout surgical retraction, most often without any disruptive patient movement from the electrical stimulation. In contrast, MEPq data must be acquired intermittently as the electrical stimulation often causes a short burst of patient movement that can be disruptive to the surgery. It is often possible for the neurophysiologist to acquire MEPq data intermittently at opportune times when the surgeon is clear of the surgical field (eg, during fluoroscopy).

Additional surgical applications for femoral nerve monitoring

Emerging femoral nerve monitoring techniques may have additional beneficial surgical applications. For example, snSSEPs may prove useful for routine intraoperative monitoring of the L3−L4 lumbar nerve roots. Commonly used peroneal and tibial nerve SSEPs may be unable to detect more rostral L3−L4 nerve root compromise as they predominantly assess the function of the L5 and S1 nerve roots, respectively [41,42]. FNEPs may also be useful in high-risk total hip arthroplasty (THA) surgery, especially for revisions, dysplasia or complex cases where the risk for femoral nerve injury is increased. Published management

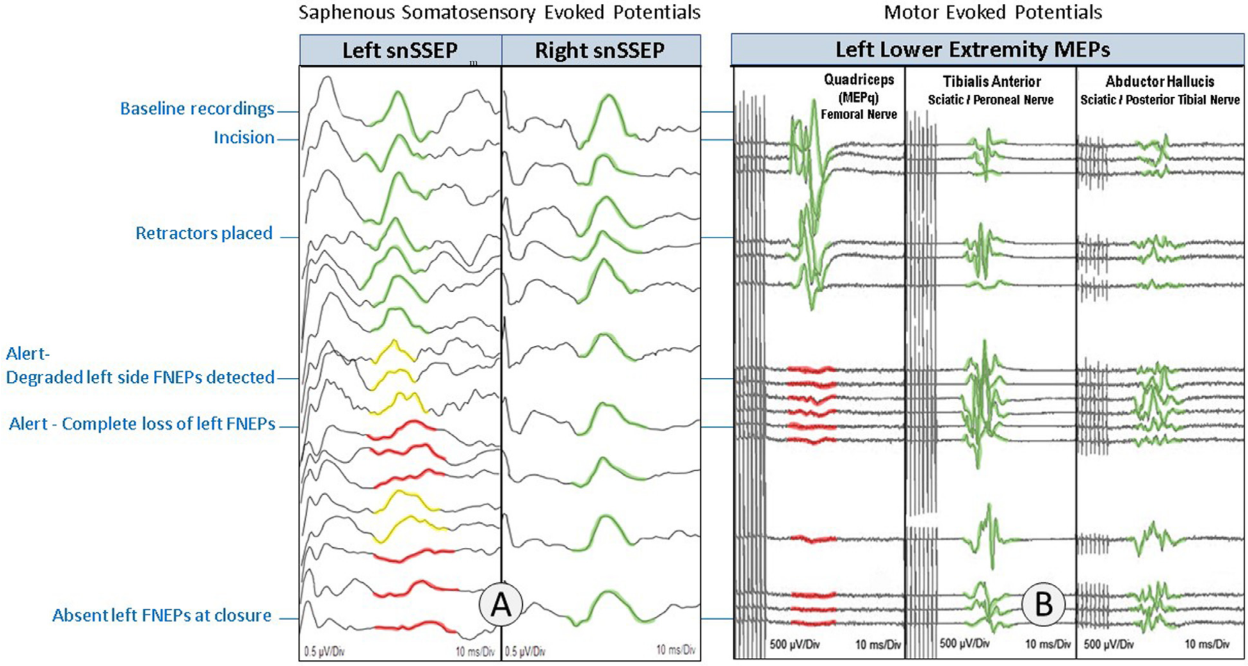

Fig. 2. Case Example 2 - Intraoperative neuromonitoring data predicts a postoperative femoral nerve injury.

A "waterfall" view shows the FNEP data chronologically from the beginning of a left L4-L5 LLIF surgery (top) until surgical closure (bottom). During surgical retraction, hyperacute femoral nerve conduction failure was detected concurrently in both the surgical-side snSSEPs and MEPq while all the control evoked potential recordings remained unchanged. (A) The left (surgical-side) snSSEP data shows evidence of femoral nerve function with robust amplitude baseline responses (green) that begin to degrade (yellow) and fluctuate in amplitude during surgical retraction until the signal is completely lost (red). In contrast, the right (non−surgical side) snSSEP data remained unchanged throughout the procedure. (B) The motor evoked potential (MEP) baseline amplitude (green) showed a complete loss of the response (red) of the quadriceps muscle recording channel (MEPq) at the same time that the left snSSEPs responses degraded. In contrast, control MEP recordings from the left tibialis anterior and abductor hallucis muscles (innervated by the peroneal and posterior tibial nerves) remained unchanged throughout the procedure. In this case, no surgical countermeasures were employed and the degraded left FNEP responses did not improve and remained absent at the time of surgical closure. As predicted by the neuromonitoring data, this patient exhibited postoperative signs of a left femoral nerve injury with medial thigh numbness and weakened knee extension (Color version of the figure is available online.).

guidelines for THA surgery have reported an incidence of femoral nerve injury ranging from 0.1% to 2.4 % [43].

Conclusion

Femoral nerve monitoring techniques include intraoperative functional assessments of both the sensory (snSSEPs) and motor (MEPq) components of the femoral nerve. Both sensory and motor evoked potential recordings should be used as the quality of the baseline data can be highly variable, and it is not uncommon to have poor or unobtainable data from one of the two monitoring modalities. Femoral nerve monitoring is technically challenging and requires a skilled and knowledgeable neurophysiologist with specialized training who can acquire useful data and interpret it appropriately. Acquisition of quality baseline evoked potential data is essential so that evidence of degraded femoral nerve function can be detected, assessed, and reported in a timely manner. Our study results suggest that the common strategy of limiting retraction duration is not effective in preventing iatrogenic femoral nerve injuries. In contrast, multimodal femoral nerve monitoring can provide surgeons with a timely alert to hyperacute femoral nerve conduction failure, so that prompt surgical countermeasures can be employed to reduce the strain on the femoral nerve during the critical period where the conduction failure is reversible.

References

[1] Ozgur BM, Aryan HE, Pimenta L, Taylor WR. Extreme Lateral Interbody Fusion (XLIF): a novel surgical technique for anterior lumbar interbody fusion. Spine J 2006;6(4):435–43. https://doi.org/10.1016/j.spinee.2005.08.012.

[2] Ahmadian A, Deukmedjian AR, Abel N, Dakwar E, Uribe JS. Analysis of lumbar plexopathies and nerve injury after lateral retroperitoneal transpsoas approach: diagnostic standardization. J Neurosurg Spine 2013;18(3):289–97. https://doi.org/10.3171/2012.11.spine12755.

[3] Davis TT, Bae HW, Mok MAJJ, Rasouli A, Delamarter RB. Lumbar plexus anatomy within the psoas muscle: implications for the transpsoas lateral approach to the l4-l5 disc. J Bone Joint Surg Am 2011;93(16):1482–7. https://doi.org/10.2106/jbjs.j.00962.

[4] Block J, Silverstein JW. The utility of Transcranial Motor Evoked Potentials (MEPs) for intraoperative monitoring of femoral nerve function for retroperioneal transpsoas access to the spine. Neurodiagn J 2014;54(4):356.

[5] Cummock MD, Vanni S, Levi AD, Yu Y, Wang MY. An analysis of postoperative thigh symptoms after minimally invasive transpsoas lumbar interbody fusion. J Neurosurg Spine 2011;15(1):11–8. https://doi.org/10.3171/2011.2.spine10374.

[6] Arnold P, Anderson K, McGuire R. The lateral transpsoas approach to the lumbar and thoracic spine: a review. Surg Neurol Int 2012;3 (Suppl 3):S198–215.
[7] Salzmann SN, Shue J, Hughes AP. Lateral lumbar interbody fusion—outcomes and complications. Curr Rev Musculoskelet Med 2017;10 (4):539–46. https://doi.org/10.1007/s12178-017-9444-1.
[8] Tohmeh AG, Rodgers WB, Peterson MD. Dynamically evoked, discrete-threshold electromyography in the extreme lateral interbody fusion approach. J Neurosurg Spine 2011;14(1):31–7. https://doi.org/10.3171/2010.9.spine09871.
[9] Park D, Lee M, Lin E, Singh K, An H, Phillips F. The relationship of intrapsoas nerves during a transpsoas approach to the lumbar spine. J Spinal Disord Tech 2010;23(4):223–8. https://doi.org/10.1097/bsd.0b013e3181a9d540.
[10] Härtl R, Joeris A, McGuire RA. Comparison of the safety outcomes between two surgical approaches for anterior lumbar fusion surgery: anterior lumbar interbody fusion (ALIF) and extreme lateral interbody fusion (ELIF). Eur Spine J 2016;25(5):1484–521. https://doi.org/10.1007/s00586-016-4407-6.
[11] Gammal ID, Spivak JM, Bendo JA. Systematic review of thigh symptoms after lateral transpsoas interbody fusion for adult patients with degenerative lumbar spine disease. Int J Spine Surg 2015;9:62. https://doi.org/10.14444/2062.
[12] Hijji FY, Narain AS, Bohl DD, et al. Lateral lumbar interbody fusion: a systematic review of complication rates. Spine J 2017;17(10):1412–9. https://doi.org/10.1016/j.spinee.2017.04.022.
[13] Pumberger M, Hughes AP, Huang RR, Sama AA, Cammisa FP, Girardi FP. Neurologic deficit following lateral lumbar interbody fusion. Eur Spine J 2011;21(6):1192–9. https://doi.org/10.1007/s00586-011-2087-9.
[14] Houten JK, Alexandre LC, Nasser R, Wollowick AL. Nerve injury during the transpsoas approach for lumbar fusion. J Neurosurg Spine 2011;15(3):280–4. https://doi.org/10.3171/2011.4.spine1127.
[15] Aichmair A, Lykissas MG, Girardi FP, et al. An institutional six-year trend analysis of the neurological outcome after lateral lumbar interbody fusion. Spine 2013;38(23). https://doi.org/10.1097/brs.0b013e3182a3d1b4.
[16] Lykissas MG, Aichmair A, Hughes AP, et al. Nerve injury after lateral lumbar interbody fusion: a review of 919 treated levels with identification of risk factors. Spine J 2014;14(5):749–58. https://doi.org/10.1016/j.spinee.2013.06.066.
[17] Rodgers WB, Gerber EJ, Patterson J. Intraoperative and early postoperative complications in extreme lateral interbody fusion. Spine 2011;36(1):26–32. https://doi.org/10.1097/brs.0b013e3181e1040a.
[18] Sofianos DMA, Briseño MR, Abrams J, Patel AA. Complications of the lateral transpsoas approach for lumbar interbody arthrodesis: a case series and literature review. Clin Orthop Relat Res 2012;470 (6):1621–32. https://doi.org/10.1007/s11999-011-2088-3.
[19] Fischer GS, Akinbiyi T, Saha S, et al. Ischemia and force sensing surgical instruments for augmenting available surgeon information. The First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, 2006. doi:10.1109/biorob.2006.1639227
[20] Li J, Shi R. Stretch-induced nerve conduction deficits in guinea pig ex vivo nerve. J Biomech 2007;40(3):569–78. https://doi.org/10.1016/j.jbiomech.2006.02.009.
[21] Ochs S, Pourmand R, Si K, Friedman RN. Stretch of mammalian nerve in vitro: effect on compound action potentials. J Peripher Nerv Syst 2000;5(4):227–35. https://doi.org/10.1046/j.1529-8027.2000.00025.x.
[22] Kiernan MC, Kaji R. Physiology and pathophysiology of myelinated nerve fibers. Handb Clin Neurol 2013:43–53. https://doi.org/10.1016/b978-0-444-52902-2.00004-7.
[23] Ebraheim NA, Mekhail AO. The infrapatellar branch of the saphenous nerve: an anatomic study. J Orthop Trauma 1997;11(3):195–9. https://doi.org/10.1097/00005131-199704000-00010.
[24] Hemler DE, Ward WK, Karstetter KW, Bryant PM. Saphenous nerve entrapment caused by pes anserine bursitis mimicking stress fracture of the tibia. Arch Phys Med Rehabil 1991;72(5):336–7.
[25] Block J, Silverstein JW, Ball HT, et al. Motor evoked potentials for femoral nerve protection in transpsoas lateral access surgery of the spine. The Neurodiagn J 2015;55(1):36–45. https://doi.org/10.1080/21646821.2015.1012456.
[26] Silverstein J, Mermelstein L, DeWal H, Basra S. Saphenous nerve somatosensory evoked potentials. Spine 2014;39(15):1254–60. https://doi.org/10.1097/brs.0000000000000357.
[27] Jain NS, Bederman SS, Phan K, Yanni DS, Guillen H, Mnatsakanyan L. Saphenous nerve somatosensory evoked potentials monitoring during lateral interbody fusion. Spine J 2015;15(10). https://doi.org/10.1016/j.spinee.2015.07.393.
[28] Chaudhary K, Speights K, McGuire K, White AP. Trans-cranial motor evoked potential detection of femoral nerve injury in transpsoas lateral lumbar interbody fusion. J Clin Monit Comput 2015;29 (5):549–54. https://doi.org/10.1007/s10877-015-9713-8.
[29] Khajavi, K, Niznik, G. Femoral nerve monitoring during lateral transpsoas approach for lumbar interbody fusion. Abstract presented at: The Annual Meeting for the International Society for the Advancement of Spine Surgery; 2015; San Diego, CA.
[30] Silverstein, JW, Block, J, Goldstein, M, Madhok, R, Basra Mermelstein, L, DeWal, H. Preserving femoral nerve function: A multimodal neuromonitoring approach in transpsoas lateral access to the spine. Abstract presented at: The Annual Meeting for ISASS; 2015; San Diego, CA.
[31] Silverstein, JW, Block, J, Madhok, R, Goldstein, M, Basra, S, Mermelstein, L, et al. Alerts for femoral nerve monitoring during transpsoas lateral lumbar interbody fusion procedures. Abstract presented at: The Annual Meeting for ISASS; 2016; Las Vegas, NV.
[32] Riley MR, Doan AT, Vogel RW, Aguirre AO, Pieri KS, Scheid EH. Use of motor evoked potentials during lateral lumbar interbody fusion reduces postoperative deficits. Spine J 2018;18(10):1763–78. https://doi.org/10.1016/j.spinee.2018.02.024.
[33] Silverstein, JW, Block, J, Goldstein, M, DeWal, H, Zook, J, Slosar, P, et al. Femoral nerve protection during lateral lumbar interbody fusion (llif). abstract presented at: the annual meeting for ISASS; 2017; Boca Raton, FL.
[34] Bederman SS, Jain N, Yanni D, Guillen H, Lilit M. Saphenous nerve somatosensory evoked potentials monitoring during lateral interbody fusion. Global Spine J 2015;5. https://doi.org/10.1055/s-0035-1554571.
[35] Berends HI, Journée HL, Rácz I, van Loon J, Härtl R, Spruit M. Multimodality intraoperative neuromonitoring in extreme lateral interbody fusion. Transcranial electrical stimulation as indispensable rearview. Eur Spine J 2015;25(5):1581–6. https://doi.org/10.1007/s00586-015-4182-9.
[36] Jain N, Alluri R, Phan K, Yanni D, Alvarez A, Guillen H, et al. Saphenous nerve somatosensory-evoked potentials monitoring during lateral interbody fusion. Global Spine J 2020:219256822092297. https://doi.org/10.1177/2192568220922979.
[37] Anloague PA, Huijbregts P. Anatomical variations of the lumbar plexus: a descriptive anatomy study with proposed clinical implications. J Man Manip Ther 2009;17(4). https://doi.org/10.1179/106698109791352201.
[38] Matejčík V. Anatomical variations of lumbosacral plexus. Surg Radiol Anat 2009;32(4):409–14. https://doi.org/10.1007/s00276-009-0546-3.
[39] Gandhia K, Joshib S, joshic S, Siddiquid A, Jalajd A. Lumbar plexus and its variations. J Anat Soc India 2013;62:47–51. https://doi.org/10.1016/S0003-2778(13)80012-3.
[40] Anandhi PG, Alagavenkatesan VN, Pushpa P, Shridharan P. A study to document the formation of lumbar plexus, its branching pattern, variations and its relation with psoas major muscle. Int J Contemp Med Res 2018;5(11). https://doi.org/10.21276/ijcmr.2018.5.11.32.

[41] Kim DH, Midha R, Murovic JA, Spinner RJ. Saphenous Nerve Block. In: Kline and Hudson's Nerve Injuries. Philadelphia: W.B. Saunders; 2008.

[42] Robinson LR, Slimp JC, Anderson PA, Stolov WC. The efficacy of femoral nerve intraoperative somatosensory evoked potentials during surgical treatment of thoracolumbar fractures. Spine 1993;18 (13):1793–7. https://doi.org/10.1097/00007632-199310000-00013.

[43] Fox AJ, Bedi A, Wanivenhaus F, Sculco TP, Fox JS. Femoral neuropathy following total hip arthroplasty: review and management guidelines. Acta Orthop Belg 2012;78(2):145–51.