Clinical Neurophysiology 123 (2012) 1465–1470

Contents lists available at SciVerse ScienceDirect

Clinical Neurophysiology

journal homepage: www.elsevier.com/locate/clinph

Pattern-specific changes and discordant prognostic values of individual leg-muscle motor evoked potentials during spinal surgery

Sung-Min Kim [a,b], Hyeran Yang [b], Soon-Bu Park [b], Suk Geun Han [b], Kun-Woo Park [a,c,e], Sang Hoon Yoon [a,d,e], Seung-Jae Hyun [a,d,e], Hyun-Jib Kim [a,d,e], Kyung Seok Park [a,b,e,*], Kwang-Woo Lee [a]

[a] *Department of Neurology, Seoul National University, College of Medicine, Seoul, Republic of Korea*
[b] *Department of Neurology, Seoul National University, Bundang Hospital, Gyeonggi, Republic of Korea*
[c] *Department of Orthopedics, Seoul National University, Bundang Hospital, Gyeonggi, Republic of Korea*
[d] *Department of Neurosurgery, Seoul National University, Bundang Hospital, Gyeonggi, Republic of Korea*
[e] *Spine Center, Seoul National University, Bundang Hospital, Gyeonggi, Republic of Korea*

ARTICLE INFO

Article history:
Accepted 27 November 2011
Available online 9 January 2012

Keywords:
Intra-operative monitoring
Motor evoked potential
Abductor hallucis
Tibialis anterior
Spinal surgery

HIGHLIGHTS

- Muscle motor evoked potentials (mMEPs) were generated at a high rate in the abductor hallucis (AH) and had high positive predictive values for sustained postoperative motor deficits.
- However, mMEPs in the tibialis anterior were more sensitive in detecting perioperative neural damage and in predicting sustained postoperative motor deficits than mMEPs in the AH.
- The interpretations of intra-operative mMEPs should be individualised according to the type of muscles recorded, and a tailored approach using multi-muscle recordings may contribute to better outcomes for spinal surgery.

ABSTRACT

Objective: The aim of the study is to evaluate the efficacy of muscle motor evoked potentials (mMEPs) in individual leg muscles for spinal surgery monitoring.

Methods: Data were obtained from 209 patients who underwent spine surgery with intra-operative mMEP monitoring in the tibialis anterior (TA) and abductor hallucis (AH) muscles. The mMEP generation, pattern-specific mMEP loss and recovery, and the accuracy of individual mMEP changes in predicting postoperative motor deficit were assessed.

Results: Generation rate of mMEPs was higher in the AH than in the TA ($p < 0.001$). The mMEP in the TA was more sensitive in detecting mMEP loss than in the AH ($p < 0.001$); however, mMEP in the AH was more sensitive in detecting mMEP recovery ($p < 0.001$). The mMEPs in the TA had high sensitivity in predicting sustained postoperative motor deficits. By contrast, mMEPs in the AH showed a high positive predictive value.

Conclusions: Although mMEPs were generated at a high rate in the AH, mMEP in the TA can play an important complementary role in intra-operative mMEP monitoring, because mMEP in the TA can be more sensitive to potential neural damage.

Significance: Using a combination of muscles with individual sensitivities and clinical significances will improve intra-operative mMEP monitoring strategies.

1. Introduction

Transcranial electric motor evoked potential (MEP) has been in use since the development of a stimulator that allowed electrical stimulation to pass through the skull (Rodi and Vodusek, 2001), and it is widely accepted as the most important tool for intra-operative corticospinal tract monitoring (Deletis and Sala, 2008). The potentials evoked by transcranial electric stimulation can be recorded from the limb muscles (muscle motor evoked potentials, mMEPs) or directly from the spinal cord (D-waves) (Kothbauer et al., 1998; Sala et al., 2006; Deletis and Sala, 2008). Despite several promising results of the studies on D-wave monitoring during surgeries for intramedullary spinal cord tumors (Kothbauer

---

* Corresponding author at: Department of Neurology, Seoul National University, College of Medicine, Yongon Dong, Jong Ro Gu, Seoul 110-744, Republic of Korea. Tel.: +82 31 787 7466.

E-mail address: pks1126@chol.com (K.S. Park).

1388-2457/$36.00 © 2011 International Federation of Clinical Neurophysiology. Published by Elsevier Ireland Ltd. All rights reserved.
doi:10.1016/j.clinph.2011.11.035

et al., 1998; Sala et al., 2006), mMEP monitoring continues to be a valuable tool. This is because mMEP needs no epidural electrode, it has a higher generation rate of MEP, and it is more accurate in monitoring for scoliosis surgery (Ulkatan et al., 2006) and aortic aneurysm surgery (MacDonald and Janusz, 2002) than D-wave.

A previous animal study has shown that the cortical projections to the leg muscles are most extensive in the intrinsic foot muscles and second most extensive in the tibialis anterior (TA) muscles (Jankowska et al., 1975). Therefore, the abductor hallucis (AH) and, alternatively, the tibialis anterior (TA) have been regarded as the optimal leg muscles for mMEP recording (Nuwer et al., 1995; Deletis and Sala, 2008; Husain, 2008). However, the clinical utility of this strategy, based on experimental data, has not been fully evaluated in patients.

We hypothesised that the mMEPs recorded from the AH might have a higher yield for mMEP generation but could be less sensitive to perioperative corticospinal injuries and also less sensitive in predicting postoperative motor deficits compared with those recorded from the TA. Because the corticospinal fiber innervations of the AH is richer than that of the TA (Jankowska et al., 1975).

2. Methods

2.1. Patients

We screened 213 patients between January 2010 and February 2011. Inclusion criteria were patients who: (1) underwent spinal surgery; (2) had intra-operative transcranial electric mMEP monitoring recorded in both AH and TA muscles; and (3) received total intravenous anaesthesia (TIVA) with propofol and remifentanil. Exclusion criteria were: (1) patients who received inhaled anaesthesia ($n = 3$) or (2) continuous infusion of neuromuscular blockade ($n = 1$). The final analytical sample included 209 patients and 418 leg recordings.

Neurological examinations of the right and left lower extremities were conducted individually. Motor function was assessed before surgery, 24 h after surgery and at 1 month after surgery. Worsening in the Medical Research Council (MRC) motor grade score (Medical Research Council, 1976) of any leg muscle compared with the preoperative score was defined as a significant postoperative motor deficit. Postoperative motor deficit was classified as transient (present at 24 h after surgery but fully recovered at 1 month after surgery) or sustained (present at 24 h after surgery and not fully recovered at 1 month after surgery). The study was approved by the Institutional Review Board (IRB) of Seoul National University Bundang Hospital (IRB NO.: B-1104-125-109).

2.2. Anaesthesia

TIVA with propofol and remifentanil was used to maintain anaesthesia. Neuromuscular blockade was induced just before intubation, to avoid a possible confounding effect of mMEP reduction (Kothbauer et al., 1997).

2.3. Muscle motor evoked potentials (mMEPs)

Transcranial electric stimulation was delivered using subcutaneous needle electrodes. In accordance with the international 10–20 electroencephalogram (EEG) system, C1 anode and C2 cathode pairs were used for stimulation of the left hemisphere and the reverse arrangement was used for stimulation of the right hemisphere. Trains of five square-wave stimuli (pulse duration 50 μs) were delivered at an interstimulus interval of 2 ms and intensity of 300–500 V (Sala et al., 2006; Quraishi et al., 2009; Yeon et al., 2010). Elicited mMEPs were recorded from the AH and TA in the lower extremities (Jankowska et al., 1975; Deletis and Sala, 2008) using a D185 stimulator (Digitimer Ltd., Wel-wyn Garden City, Hertfordshire, UK) and a Protektor^{TM} intra-operative monitor (Xltek Ltd., Ontario, Canada).

The high intertrial variability of mMEP amplitudes (Burke et al., 1995; Woodforth et al., 1996) and the fact that mMEP loss has been strongly associated with postoperative motor deficits in spinal surgeries (MacDonald and Janusz, 2002; Sala et al., 2006; Ulkatan et al., 2006; Deletis and Sala, 2008; Quraishi et al., 2009) led us to use the ‘presence or absence’ of a response as a warning criterion for significant mMEP changes.

Pattern-specific mMEP loss and recovery were analysed to assess whether the TA and the AH muscle recordings differed in sensitivity to perioperative neural damage and/or recovery (Table 1). First, an mMEP loss or recovery was classified as a ‘sequential change’ when the mMEP change in one muscle recording preceded that in the other muscle, as an ‘isolate change’ when the mMEP change was observed in one muscle recording only, or ‘simultaneous change’ when mMEP changes were simultaneously observed in the TA and AH recordings. Second, change in mMEP was classified as ‘TA-sensitive pattern’ when the mMEP change in the TA preceded that in the AH (‘sequential change’), or when the mMEP change was observed only in the TA (‘isolated change’). The ‘AH-sensitive pattern’ was defined as the opposite of the ‘TA-sensitive pattern’ (Table 1). The mMEP loss pattern was assessed in legs in which baseline mMEPs were generated in both the TA and AH, and mMEP recovery pattern was assessed in legs in which mMEPs were lost in both muscles during surgery.

Furthermore, mMEP losses were regarded as reversible when they recovered at the end of surgery (spontaneously or after correction of the presumed cause) or as irreversible when mMEP loss persisted at the end of surgery (Szelényi et al., 2010). Sensitivity, specificity, positive predictive value and negative predictive value of the mMEP loss were measured in individual muscles to predict postoperative motor deficits.

2.4. Statistical analysis

Pearson’s *chi*-squared test and Fisher’s exact test were used to compare mMEP generation and the frequency of pattern-specific mMEP changes in individual muscles, respectively. Statistical analyses were conducted using Predictive Analytics SoftWare (PASW, ver. 18; SPSS Inc., Chicago, IL, USA).

3. Results

The generation rate of mMEPs and patterns of mMEP losses are summarised in Fig. 1.

The overall generation rate of any mMEP in the leg was 80.1% and no leg mMEP was observed in 19.9% of the recordings. mMEPs were generated in both the TA and AH in 59.1% of the recordings (Fig. 1). The generation rate of mMEPs was significantly higher ($p < 0.001$) in the AH than in the TA (Fig. 1).

Of the 247 leg recordings in which mMEPs were recorded in both TA and AH, 17 showed mMEP losses during surgery (Figs. 1–3). The clinical characteristics of these 17 leg recordings are summarised in Table 2. A pattern-specific analysis of the mMEP loss was performed on those recordings using the classification criteria shown in Table 1, and revealed that mMEP in the TA was more sensitive in detecting mMEP loss than in the AH ($p < 0.001$; Fig. 3).

Of the 11 leg recordings in which mMEPs were lost in both the TA and AH during surgery (i.e., six ‘sequential losses’ with TA-sensitive pattern and five ‘simultaneous losses’; see Fig. 3), recoveries (reversible mMEP loss) were observed in nine recordings (Figs. 4 and 5). A pattern-specific analysis of the mMEP recovery (Table 1)