Journal of the Neurological Sciences 284 (2009) 46–51

Contents lists available at ScienceDirect

Journal of the Neurological Sciences

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

Magnetic stimulation of the cauda equina in the spinal canal with a flat, large round coil

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ARTICLE INFO

Article history:
Received 10 January 2009
Received in revised form 27 March 2009
Accepted 2 April 2009
Available online 1 May 2009

Keywords:
Magnetic stimulation
Compound muscle action potential
Motor evoked potential
Cauda equina
Normal values

ABSTRACT

Magnetic round coil stimulation over the spinal enlargement activates the spinal nerves at the neuro-foramina level. However, activation of the cauda equina in the spinal canal has never been described in the literature. This study, for which 40 healthy subjects were recruited, activated the cauda equina using a round 20-cm-diameter coil designated as a Magnetic Augmented Translumbosacral Stimulation (MATS) coil. Magnetic stimulation placing the edge of the coil over the L1 and L3 spinous processes elicited compound muscle action potentials (CMAPs) from the abductor hallucis muscle. The CMAPs were compared with those elicited through high-voltage electrical stimulation. The CMAP latencies to L1 level MATS coil stimulation were not significantly different from those evoked by electrical stimulation at the same level. The CMAP latencies to L3 level MATS coil stimulation were varied in each subject. In fact, the L1 level MATS coil stimulation is considered to activate the cauda equina at the root exit site from the conus medullaris; the L3 level MATS coil stimulation activates some mid-part of the cauda equina or the distal cauda equina by spreading current. The MATS coil facilitates evaluation of spinal nerve conduction in the cauda equina.

1. Introduction

Ugawa et al. reported that spinal nerves can be activated by placing a magnetic coil over the cervical or lumbar spinal enlargement (magnetic stimulation at the neuro-foramina level) [1,2]. Magnetic stimulation at the neuro-foramina level sometimes provides important physiological information that is unobtainable through conventional electrical nerve conduction studies. Such information is useful for detecting focal demyelinating lesions at some proximal sites of peripheral nerves [3,4]. We have confirmed that, using improved magnetic stimulators and coils [5,6], supramaximal stimulation can be performed with magnetic stimulation at the neuro-foramina level in almost all healthy subjects. Especially for lower limb muscles, supramaximal stimulation can be accomplished using a flat, round, 20-cm-diameter coil designated as a Magnetic Augmented Translumbosacral Stimulation (MATS) coil, which can produce great eddy currents in deeper portions of the body [6]. Therefore, the amplitude, area, and latency of compound muscle action potentials (CMAPs) can be evaluated from peripheral parts up to the neuro-foramina level.

Cervical spinal nerves in the spinal canal are short. Their short conduction time rarely has clinical importance. However, lumbosacral spinal nerves in the spinal canal (i.e. cauda equina) sometimes have clinical importance because they are long and are frequently affected by disorders. However, activation of the cauda equina in the spinal canal by a round coil has never been reported (the proximal part of the cauda equina in spinal canal can be activated by an eight-shaped coil) [1,7,8]. Herein, we describe that proximal and intermediate parts of the cauda equina can be activated reliably using the MATS coil. To ensure the supramaximal stimulation and to localize the site of activation, we compare CMAPs evoked by magnetic stimulation with those by high-voltage electrical stimulation. Additionally, we describe normal values of the conduction time of the cauda equina and we present a patient in whom magnetic stimulation with a MATS coil gave us clinically useful information.

2. Subjects and methods

2.1. Subjects

Subjects were 40 healthy volunteers (20 men and 20 women) with no history of peripheral neuropathy, neuromuscular disease, or other medical problem including diabetes mellitus. The subjects' respective ages and body heights were 40.6 ± 13.5 (mean ± standard deviation (SD); range 23–73) years and 163.3 ± 8.4 (147–182) cm. We also

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doi:10.1016/j.jns.2009.04.003

studied a patient with primary malignant lymphoma involving the cauda equina. Details of the patients are presented in the Results section.

Informed consent to participate in this study was obtained from all subjects. The protocol was approved by the Ethics Committee of The University of Tokyo. The experiments were conducted in accordance with the ethical standards of the Declaration of Helsinki.

2.2. Recording

During the examination, subjects lay comfortably on a bed in a prone position. The CMAPs were recorded from the right abductor hallucis muscle (AH). This muscle was selected because of its negligible volume conduction from other muscles. Disposable silver–silver chloride disc electrodes of 9 mm diameter were placed in a belly tendon montage over AH. Signals were amplified by filters set at 20 Hz and 3 kHz and were recorded using a computer (Neuropack MEB-9100; Nihon Kohden Corp., Japan). The skin temperature was maintained at around 32–33 °C. The following parameters were measured from each CMAP using an algorithm: peak-to-peak amplitude (mV), negative area (mV ms), and onset latency (ms). The data for each parameter are shown in mean ± standard deviation (SD) unless otherwise described. For the discussion presented herein, we abbreviated the CMAP elicited by supramaximal stimulation as supramaximal CMAP.

2.3. Devices of stimulation

Magnetic stimulation was performed using a monophasic stimulator (Magstim 200; The Magstim Co., UK) connected to a MATS coil (diameter 20 cm, 0.98 T, Serial No. ENG SPC SP15858, this coil is available as a customer-designed coil; The Magstim Co, UK) [6]. The eddy current pulse induced by this stimulator was 1.0 ms in duration with a rising time of 0.1 ms. As described in this paper, we used the terms of MATS coil stimulation for magnetic stimulation using a MATS coil. High-voltage electrical stimulation was performed using an electrical stimulator (Digitimer D 180A; Digitimer Ltd., UK). This stimulator gave a spike pulse with a fast rise time and an exponential decay (nominal time constant of 100 μs). To elicit *F*-waves, a constant current square wave pulse with duration of 0.2 ms was given to the posterior tibial nerve at the ankle (Nihon Kohden Corp., Japan).

2.3.1. Experiment I. Optimal induced current direction at the L1 level

Six subjects participated in this experiment. Magnetic stimulation at the level of the first lumbar (L1) spinous process was performed. The MATS coil was always placed from the midline to the left side of the body (the opposite side from the recorded muscle) to prevent some non-target parts of the coil from activating distal peripheral nerves for the target AH. The edge of coil was positioned over the L1 spinous process. The stimulus intensity was adjusted to the intensity of the maximal stimulator output at which the intensity never gave supramaximal stimulation (see Results section). Magnetic stimulation was performed with the induced current flowing either upward or downward in the body (the induced current direction is defined as the tangential direction of coil winding over the activation site, dashed line in Fig. 1). With each current direction, three CMAPs were evoked and the mean CMAPs were compared between different directions of the induced currents. The optimal induced current direction was defined as the direction in which the largest CMAP was elicited.

2.3.2. Experiment II. Comparison of CMAP sizes between magnetic stimulation and electrical stimulation

In this experiment, 13 subjects participated. The amplitude and area of CMAP to magnetic stimulation were compared with those of electrical stimulation.

2.3.2.1. Magnetic stimulation. For magnetic stimulation at the levels of L1 and L3, the edge of the coil was positioned over L1 or L3 spinous process. At the L1 level, the MATS coil was placed using the optimal induced current direction, i.e. cranially induced current (see Results section) determined in Experiment I. At the L3 level, we used the caudally directed induced current to stimulate the cauda equina according to the previous study, which shows optimal induced current direction in magnetic round coil stimulation of peripheral nerves [9]. At both levels, the intensity was increased gradually to the maximal stimulator output (100%). We considered that supramaximal stimulation was achieved only when the size of superimposed CMAPs was saturated before the stimulus intensity reached maximal stimulator output. More than three CMAPs were collected at each level to confirm reproducibility.

2.3.2.2. Electrical stimulation. For high-voltage electrical stimulation of the cauda equina, a cathode was placed over the L1 or L3 spinous process and an anode was placed at least 5 cm rostral to it. At both levels, the intensity was increased gradually until supramaximal stimulation was confirmed.

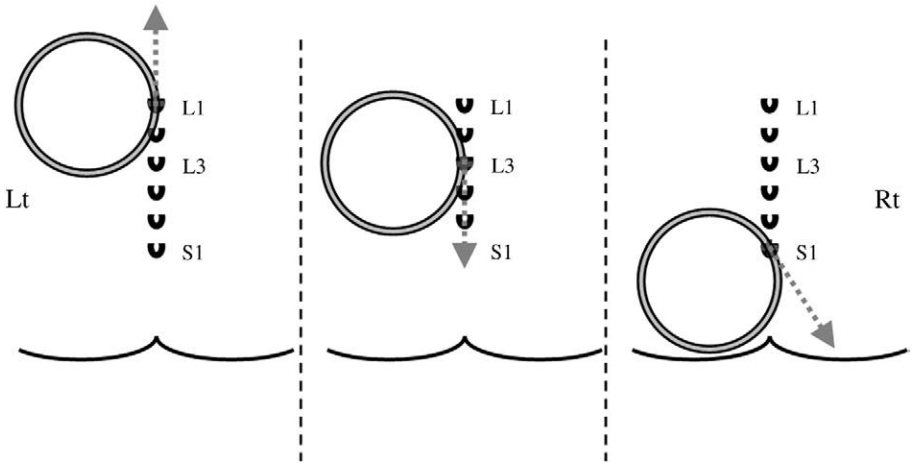

Fig. 1. Position of the MATS coil in magnetic stimulation of cauda equina. The coil edge was positioned over the L1, L3, and S1 spinous process. The induced current directions defined as the tangential direction of coil winding over the activation site are shown (dashed lines). To calculate the CECT, L1 and S1 level MATS coil stimulations were performed.