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Research Article

Motor Conduction Time Along the Cauda Equina at Rest and After Walking Following Electrical and Magnetic Stimulation

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Abstract

Introduction: Intermittent neurogenic claudication because of lumbosacral spinal stenosis (LSS) usually begins in people over 60 years. Aim is to measure motor conduction time (CT) in the cauda equina (CE) in healthy people and patients with intermittent neurogenic claudication because of LSS at rest and after walking. To compare magnetic and electrical stimulation (MS and ES), and the sensitivity and specificity of both methods.

Methods: Study was randomized controlled trial. Motor CT in the CE of healthy people and patients with intermittent neurogenic claudication due to LSS at rest and after walking as well as the sensitivity and specificity of both methods were calculated.

Results: In healthy subjects, there were no statistically significant changes in CECT after ES (2.9 ms ± 1.6 ms) and MS (3.4 ms ± 1.3 ms) at rest, but it was statistically significantly longer in patients with LSS (5.2 ms ± 1.2 ms) after a 10-minute walk. The best sensitivity and specificity were after MS of CE after a 10-minute walk.

Conclusions: We noted statistically significantly prolonged CECT in patients with intermittent neurogenic claudication due to LSS after walking compared to being at rest and compared to healthy participants. We got the best sensitivity and specificity after MS of the CE after a 10-minute walk. Measuring CECT could become a useful routine non-invasive method, which could help physicians to choose an optimal way of treatment for people with intermittent neurogenic claudication because of LSS. However, the number of participants was small, and it would be

advisable to conduct a study with a larger number of participants.

Keywords: Cauda equina; Conduction time; F wave; Lumbosacral spinal stenosis; Percutaneous electrical stimulation; Percutaneous magnetic stimulation

1. Introduction

Lumbosacral spinal stenosis (LSS) is a narrowing of the spinal canal, which compresses the nerves travelling through the lower back into the lower limbs [1-4]. It appears more often in older people as a degenerative condition, but can also affect younger patients, due to developmental causes [1-4]. Symptomatic patients with LSS often have intermittent neurogenic claudication, which they feel and describe in different ways, and with diagnostic procedures at rest, it is difficult to evaluate it objectively. A decision about an appropriate method of treatment is, therefore, complicated [1-23]. Measurement of conduction in the CE at rest and after walking may be a valuable tool in LSS work-up because nowadays diagnosis is usually made at rest and it does not detect signs of intermittent neurogenic claudication due to LSS [1, 24-27]. Various methods have been employed to evaluate conduction in CE. Stimulation of the CE was used, either magnetic [24, 28-34] or electrical, to elicit motor responses in the lower limbs, and to measure motor CT at rest. The aim was to measure motor CT in the CE in healthy people and patients with intermittent neurogenic claudication because of LSS at rest and after walking, with percutaneous MS and ES, and to compare the sensitivity and specificity of both methods.

2. Methods

Our study was randomized controlled trial. It included 36 healthy volunteers without clinically manifesting disease or injury to the lumbosacral nerves, and without any systemic illness known to cause peripheral nerve damage (e.g. diabetes mellitus), 18 women and 18 men, 19 to 68 years old, and 25 patients with typical symptoms of LSS, 11 women and 14 men, 63.8 ± 9.9 years old. Patients with LSS had a clear history of intermittent neurogenic claudication (symptoms appeared after at least 500 metres of walking and disappeared at rest after flexing forward or sitting down) and LSS proven by imaging diagnostics. The protocol of the study was approved by the national ethics committee. We used two methods for measuring CT in the CE: percutaneous ES using the Digitimer D180 and percutaneous MS of the CE using the Magstim 200 with a figure-of-eight cone coil. ES was performed using a pair of disposable disc electrodes (CareFusion disc electrodes) attached to the subject's back, the cathode at L1, and then the S1 spinous process, and the anode 10 cm cranially. ES started at 10% maximum output intensity and was gradually increased in 5% steps until repeatable compound muscle action potential (CMAP) was observed, and after that the stimulus was increased to the point tolerated by the subject. MS was performed with the centre of the figure-of-eight magnetic coil (MC) first placed over S1, and then over the L1 spinous process, with a caudally directed MC junction current. MS started at 30% output of the stimulator, and gradually increased in 5% steps up to at least 90%, as tolerated by the subject.

Recording was performed using a Synergy EMG machine, and Digitimer (short duration of the stimulus) and Magstim stimulators were used for ES and MS respectively. To record from the abductor hallucis muscle disposable disc electrodes (CareFusion disc electrodes) were attached bilaterally beneath the sustentaculum tali (active), and over the first metatarsophalangeal joint (reference). Amplifier filtering was set at 2-20 kHz and the time of analysis was either 50 ms or 100 ms. Latencies were measured manually at the gain of 500 μV per division. Motor CT

in the CE was calculated at rest and after 10 minutes of walking. The participants were in a half-sitting position on the examination table at MS, and in a supine position at ES. CMAP latencies were recorded, and CT in the CE was calculated at rest and after 10 minutes of walking. The arithmetic means of right and left recordings were calculated and taken for further analysis. Prism Graph Pad software was used for statistical analysis, performing descriptive statistics, the normality test, t-test, and repeated ANOVA and ANCOVA measures. We expressed the data as a mean ± standard deviation. The influence of age, height, and weight and body mass index on conduction parameters was calculated with the Pearson correlation analysis. Our hypotheses were that there would not be a statistically significant difference between CECT after ES and MS in healthy subjects at rest, nor in CECT of healthy subjects and patients at rest or in CECT of healthy subjects at rest and after walking, but there would be a statistically significant difference in CECT of patients with LSS at rest and after walking; after walking it would be statistically significantly longer. Latencies of CMAP after MS and ES were recorded. A CT in the CE was obtained by subtracting S1 latency from L1 latency.

3. Results

The ES CMAP was recorded in 30 subjects. S1 and L1 MS CMAPs were performed in 36 subjects. CECT in healthy subjects was 3.4 ± 1.2 ms after MS and 3.4 ± 1.4 ms after ES (Table 1).

We checked the differences between values of CECT after MS at rest and after a 10-minute walk in healthy participants. With t-test, we revealed no statistically significant differences in CECT in 7 subjects at rest and after a 10-minute walk ($t(4)=0.655$, $p=0.548$). We checked the influence of gender, age, height, and weight and body mass index on CECT. With an independent t-test, we established that gender had no influence on CECT (neither after ES nor MS). The weight had an influence on CECT, which was longer in heavier subjects. With a paired t-test, we compared the same conduction parameters after MS of 23 patients with LSS and healthy subjects. Patients with LSS had no statistically significant differences between the results of the left and right side of the body ($p>0.05$). In order to show results more systematically, we used the mean of both sides in the further analysis. Later, we compared CECT after MS at rest and after a 10-minute walk. We used ANOVA in 17 patients with LSS at rest and 6 patients with LSS after a 10-minute walk. At rest there was no statistically significant difference between CECT of patients with LSS after ES and MS. With an independent t-test, we found no statistically significant influence of gender on CECT ($p>0.05$). We checked a potential influence of age, height, and weight and body mass index on CECT with Pearson correlation analysis. Age, height, weight, and body mass index had no statistically significant influence on CECT ($p>0.05$). There was a statistically significant difference in CECT after MS at rest and after a 10-minute walk ($p=0.045$) in patients with LSS (Table 2).

At rest, there was no statistically significant difference in the CECT between patients with LSS and healthy subjects ($p>0.05$). In results after a 10-minute walk, there was a statistically significant difference in CECT after MS between patients with LSS and healthy subjects (Table 3). The difference also remained statistically significant after checking the influence of age and height.

CEMCT [ms] of healthy subjects at rest	Mean	Standard deviation
after ES (n=34)	3.4	1.4
after MS (n=30)	3.4	1.2
T (30)=0.655, p=0.548		

Table 1: Difference in the CECT after ES and MS in healthy subjects at rest.

CEMCT after MS in patients [ms]	Mean	Standard deviation
at rest (n=11)	3.5	1.7
after 10-minute walk (n=6)	5.2	1.2
T (15)=-2.191, p=0.045		

Table 2: Difference in the CECT after MS in patients with LSS at rest and after a 10-minute walk.

Difference		Mean	Standard deviation
CEMCT after MS at rest [ms]	patients (n = 17)	3.9	2.3
	healthy (n = 7)	2.9	1.4
	T (21) = 1.114, p = 0.277		
CEMCT after MS after a 10-minute walk [ms]	patients (n = 6)	5.2	1.2
	healthy (n = 5)	2.7	1.4
	T (9) = 3.227, p = 0.010		

Table 3: Difference between patients with LSS and healthy subjects after MS of the CE at rest and after a 10-minute walk.

The sensitivity of the ES of healthy volunteers and patients with LSS at rest is 69%, and specificity is 64% at a limit of 3.2 ms. The sensitivity of MS in healthy subjects and patients with LSS at rest is 56%, and specificity is 75% at a limit of 4.0 ms. The sensitivity of MS in healthy subjects and patients with LSS after a 10-minute walk was 100%, and specificity 80% at the limit of 3.7 ms, which is statistically significant.

4. Discussion

Our study suggests that [1] at rest CECT after MS is not significantly different (longer) than CECT after ES, [2] after a 10-minute walk CECT in healthy people after MS is not significantly different (longer) than CECT after MS at rest, [3] after a 10-minute walk CECT in patients with LSS after MS is significantly longer than CECT after MS in patients with LSS at rest [26]. Mean CECT after MS in our study was 3.3 ± 1.2 ms, ranging 0.9-6.5 ms. Our results are similar to the results of other authors [24, 30, 32]. At a presumed mean length of the filum terminale of about 20 cm, and conduction velocity in the CE nerve fibres of about 70 m/s, expected CT in the CE would be 2.9 ms. In some subjects, the CT was as short as 0.1 ms after MS, suggesting that either proximal stimulation excited CE too distally or distal stimulation too proximally or both. CMAPs after ES

and MS of the CE, as recorded from the abductor hallucis muscle, tend to be of the same basic waveform as CMAP recorded after stimulation of PTN. Recording from the abductor hallucis muscle ensures a relatively high selectivity of detection, precluding contamination with CMAPs of other (foot) muscles. As the H reflex is not common in the abductor hallucis muscle after peripheral stimulation, it may be present when stimulating proximally, as shown by Hofstoetter et al. [29]. The appearance of the F wave under proximal stimulation is unlikely, due to submaximal stimulus in both ES and MS. This allows us to assume that waveforms after proximal stimulation are composed of CMAP with some admixture of H reflex. This does not affect latency of the CMAP but may well affect its amplitude. Also expected in proximal stimulation is a desynchronisation of CMAP, producing its longer duration, more complex waveform, and lower amplitude [29].

There was no statistically significant difference between CECT after MS and ES in healthy participants. At rest, CECT of healthy subjects after MS was 3.4 ± 1.3 ms. In some subjects CECT after ES was only 0.1 ms and 0.9 ms after MS, which could mean that proximal stimulation excited CE too distally or distal stimulation excited CE too proximally or both. Matsumoto et al. measured CECT 3.7 (SD 0.7) ms after MS in 30 healthy subjects, of the mean age of 40.1 (SD 13.1) years and the mean height of 163.2 (SD 8.3) cm [30], Maccabee et al. [32] 3.5 ms, and Maegaki et al. [35] 3.3 ms in their study with children. In healthy subjects, there was no statistically significant difference in CECT at rest and after a 10-minute walk. This result was expected because healthy subjects had no parameters which could importantly influence CE motor conduction speed. During sports activity body structures get warmer and, thereafter, CE conduction speed could get higher and consequently CECT could get slightly shorter, but a statistically significant influence has not yet been reported in the literature [36-39].

Secil et al. made a laminar ES of the lumbar spine at the L1-L5 segments with the needle electrode in 21 patients with LSS and 15 healthy subjects [1]. Responses were recorded bilaterally from the gastrocnemius muscles and CECT was calculated as the difference between M-wave latencies after ES at L1 and L5 [1]. The mean CECT was 3.5 ± 1.1 ms in patients with LSS and 1.4 ± 0.7 ms in healthy subjects, and the difference was statistically significant [1]. If we calculate the mean conduction speed in the CE with their CECT and CE length 20 cm, we get a conduction speed in the CE of 57.1 m/s in patients, and 142.8 m/s in healthy subjects. The last value significantly surpasses normal physiological values [40]. In our study, there was a statistically significant difference between CECT in patients and healthy subjects after walking as well (in our study both values were longer), but not at rest.

Senocak et al. used MS with a circular coil for nerve roots at L1-L2 and L5-S1 [24] (diameter 90 mm) in 15 patients with LSS (aged 52.9 years (SD 9.8)) and 20 healthy subjects of similar age (aged 46.7 years (SD 11.5)) lumbar spinal roots. Responses were recorded bilaterally from the gastrocnemius, soleus and tibialis anterior muscles with bipolar percutaneous electrodes [24]. The CECT was calculated as the difference of M-wave latencies after MS at spinal levels L1 and L5 [24]. There was no sginficant statistical difference between the mean cauda equina motor conduction time in patients (3.57 ms (SD 2.22)) compared to 1.97 ms (SD 0.67) in healthy subjects and they did not differ statistically significantly [24]. When we calculate the mean CE conduction speed with CECT in their study and length of the CE 20 cm, we get a CE conduction speed of 56.0 m/s in patients and 101.5 m/s in healthy subjects. The last value is a little higher than normal

physiological values [40]. Our subjects were younger than theirs, and our patients with LSS were older than their patients. In their study they stimulated spine roots at spinal levels L1-L2 and L5-S1, and we did at L1 and S1. Their coil was circular and ours in a figure of eight. In their study they recorded muscle responses from the gastrocnemius, soleus and tibialis anterior muscles, and we did so from the abductor hallucis muscles. In our study, there was no statistically significant difference in CECT of healthy subjects and patients with LSS at rest. After walking the difference in CECT between healthy subjects and patients with LSS in our study was statistically significant but was longer than their CT of healthy subjects and patients with LSS.

Han et al. calculated caudal CECT 4.0 (SD 0.9) ms in healthy subjects and 6.2 (SD 1.4) ms in patients with LSS after MS at spinal levels S1 and T12 in their study by measuring central motor CT after transcranial MS [31]. Han et al. measured longer CT in the CE in patients with LSS with the help of central motor conduction time, because they thought that the length of the CE is too short for reliable measurement of its CT [31]. With the help of transcranial MS, exciting at spinal segments TH12 and S1, and recording from the rectus abdominis muscle and both abductor hallucis muscles, they measured motor CT in the CE [31]. Han et al. measured caudal motor CT between segments TH12 and S1 with the help of central motor CT after transcranial magnetic stimulation, but we did this as the difference between latencies after MS at segments S1 and L1. Han et al. were recording from the rectus abdominis muscle proximally and abductor hallucis muscles distally [31]. In our study we recorded from the abductor hallucis muscle. Their caudal motor CT was longer than our CECT of healthy participants and patients at rest.

There are some methodological differences among the mentioned studies and our measured CECT. In our study, we used MS of the CE with the figure-of-eight cone coil, Secil et al. used laminar ES with needle electrodes, Senocak et al. used MS with a circular coil, and Han et al. also used transcranial MS. In other studies, CECT of patients was statistically significantly longer at rest, while in our study it was after walking. When we measured conduction velocity in the CE with the help of CECT in the studies of Seçil and Senoçak with co-authors, CT of healthy participants was different from physiological values. Our calculated conduction velocity in the CE and calculated velocity in the study of Han et al. are within the physiological range. Intermittent neurogenic claudication symptoms in patients with LSS tend to occur after walking [26, 41], so it is unusual that the authors mentioned could measure statistically significant CECT in patients with LSS at rest. In our study we measured longer CECT of patients with LSS after walking, but not at rest.

All subjects claimed that MS and ES are unpleasant methods. They described sensations like an electrical hit with paraesthesia and sharp pain. Most subjects chose MS as the less unpleasant method. Similar feelings of subjects are reported in the literature [30, 34]. The specificity of the MS at rest is better than that of ES; nevertheless, sensitivity of ED is somewhat better. Sensitivity and specificity of the MS are much better after a 10-minute walk and the surface below the ROC curve was statistically significant. Sensitivity and specificity of MS after a 10-minute walk were the highest, but the number of subjects was low and it would be good to conduct one more study with more subjects. In the literature there are no data on sensitivity and specificity of measuring CECT with ES or MS. All our hypotheses were true and there was no statistically significant difference between CECT after ES and MS in healthy subjects at rest, nor in CECT of healthy

subjects and patients at rest, or in CECT of healthy subjects at rest and after walking, but there was in CECT of patients with LSS at rest and after walking; after walking it was statistically significantly longer. Measuring CECT could become a useful routine non-invasive method, which could help physicians to choose an optimal way of treatment for people with intermittent neurogenic claudication because of LSS. However, the number of participants in the study was small, and it would be advisable to conduct a study with a larger number of participants.

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