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Vestibulospinal responses in motor incomplete spinal cord injury

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ABSTRACT

Objective: Postural instability limits ambulatory capacity in patients with spinal cord injury (SCI). Galvanic vestibular stimulation (GVS) was used to investigate the integrity of vestibulospinal pathways and related changes in postural responses in SCI.
Methods: Binaural bipolar galvanic stimuli of 400 ms duration and 3 mA intensity were applied in 8 motor incomplete SCI and 8 control subjects who stood facing towards the left. EMG responses were recorded from the right soleus muscle and the trajectory of the centre of pressure (CoP) was measured with a force plate.
Results: There was no difference in excitability and amplitude of the responses between the groups. However, the latency and duration of the medium latency EMG response and all CoP responses were significantly longer in the SCI group. Additionally, postural stability was reduced in the SCI group, as shown by a greater tendency to fall due to GVS.
Conclusions: Despite early EMG responses proving the basic connectivity of the direct vestibulospinal pathways, the delayed GVS responses suggest a vestibulospinal deficit in the SCI subjects.
Significance: GVS can be applied in incomplete SCI to supplement the neurological examination by revealing changes in vestibulospinal responses and impairment of postural stability.

1. Introduction

To maintain postural stability, multiple afferent inputs, such as from the visual, vestibular and somatosensory systems are required. Postural control also depends on the appropriate execution of motor responses. Thus, it is important that sensory input is integrated and converted to efferent motor outputs, which in turn are conducted down the spinal cord along different motor tracts. However, after spinal cord injury afferent and/or efferent spinal pathways may be damaged, resulting in different effects on postural stability.

Presently, the clinical examination of spinal cord injury (SCI) focuses on describing the motor and sensory deficits in order to define the neurological level and completeness of the lesion according to the standards outlined by the American Spinal Injury Association (ASIA) (Maynard et al., 1997). Although structural deficits are only indirectly assessed with this protocol, it is possible to use the ASIA scores to estimate functional outcome after SCI (Curt and Dietz, 1999). Improved diagnosis, prediction and monitoring of functional outcome rely on additional examinations such as neuroimaging, behavioural examinations and electrophysiological recordings. The latter measures include somatosensory (SSEP) and motor evoked potentials (MEP), sympathetic skin reflexes (SSR), electromyography and reflex measurements (Curt et al., 2004). To test the integrity of the corticospinal tract, MEPs elicited by transcranial magnetic stimulation can be examined (Diehl et al., 2006; Thomas and Gorassini, 2005). In addition, SSEP recordings can be applied to assess the impulse transmission of somatosensory tracts. In SCI patients, these electrophysiological methods are valuable for predicting hand- and lower limb function (Curt et al., 1998; McKay et al., 2005). However, many other ascending and descending spinal pathways, such as the vestibulospinal pathways, are not yet routinely assessed. Since the vestibulospinal pathways are involved in the control of posture and balance, their examination is of particular importance for research in motor incomplete SCI.

Abbreviations: SCI, spinal cord injury; ASIA, American Spinal Injury Association; GVS, galvanic vestibular stimulation; CoP, centre of pressure; EMG, electromyogram; MEP, motor evoked potentials; SSEP, somatosensory evoked potentials; ML, medium latency; SL, short latency; TA, tibialis anterior muscle; SO, soleus muscle.

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Through binaural bipolar transmastoid galvanic currents, equilibrium can be perturbed while other sensory input remains constant, leading to a sensory mismatch (for review, see Day et al., 2002; Fitzpatrick and Day, 2004). Such galvanic vestibular stimulation (GVS) can induce several movements of the eyes, a tilt of vertical and postural shifts (Coats, 1973; Karlberg et al., 2000; Nashner and Wolfson, 1974) as well as alterations of the walking trajectory in humans (Bent et al., 2000; Fitzpatrick et al., 1999). Depending on how much a subject is relying on vestibular input, he will more or less posturally react to a GVS-evoked sensory mismatch. GVS-elicited postural responses are also affected by the position of the head relative to the feet (Lund and Broberg, 1983) as well as electrode placement. The resultant movements of the head and body occur in the direction where the anode is placed (Coats and Stoltz, 1969; Day et al., 1997; Lund and Broberg, 1983; Nashner and Wolfson, 1974). GVS typically evokes a biphasic EMG response consisting of a short (SL) and medium latency (ML) component, which up to now have only been observed in posturally active muscles (Ali et al., 2003; Britton et al., 1993; Fitzpatrick et al., 1994b; Iles and Pisini, 1992; Nashner and Wolfson, 1974). Postural muscle activity arising shortly after GVS is assumed to have a vestibular origin and therefore provides a means for investigating the integrity of the vestibulospinal pathways (Iles et al., 2004). However, in the present study with "Vestibulospinal pathways" we refer to all spinal tracts involved in conducting a vestibular driven reaction down the spinal cord which according to literature at least partly consists of vestibulo-, reticulo-, and/or corticospinal tracts (Britton et al., 1993; Iles et al., 2004).

Beside our own research (Wydenkeller et al., 2006), so far only one study has reported the effect of GVS in individuals with SCI (Iles et al., 2004). Focusing on responses in active trunk muscles (erectores spinae) of sitting subjects, they found correlations between GVS-evoked EMG responses and neural impairment as assessed by the ASIA score. But they made no quantitative reports in SCI of GVS-elicited responses in leg muscles. Therefore, the aim of the present study was to investigate the preservation of vestibulospinal lower leg EMG responses and their relation on postural sway in ambulatory individuals with SCI.

We hypothesised that the direct lower leg EMG responses could be attenuated (delayed and reduced) as they likely depend on the integrity of the vestibulospinal pathways that can be assumed to be altered at the spinal level in incomplete SCI. In contrast, the postural sway could be differently affected, as that is additionally dependent on multiple supralesional motor events.

2. Methods

A case-control cross-sectional study with pair-wise matching was designed to examine the differences in EMG and body sway responses elicited by galvanic vestibular stimulation between ambulatory SCI and healthy control persons. All techniques were approved by the local Ethics Committee and conformed to standards set by the Declaration of Helsinki. All subjects gave informed, written consent and were permitted to leave the study at any time.

2.1. Subjects

Eight male subjects with motor incomplete SCI and eight healthy controls, matched for gender and age, participated in this study. All of them were able to stand without assistance, had normal hearing and vision, and no history of diseases of the ear or vertigo. The SCI subjects were on average 47 ± 7 years old, 1.76 ± 0.06 m tall and weighed 75 ± 16 kg. The controls were on average 47 ± 8 years old, 1.81 ± 0.05 m tall and weighed 84 ± 16 kg. Spinal cord injury was caused either by trauma (6 subjects), ischemia (1 subject) or a tumour (1 subject). All SCI subjects were paralysed incompletely with neurological lesion level between C4 and T8 and classified as ASIA impairment scale grade D (Maynard et al., 1997). Table 1 shows the neurological data of the SCI subjects. Questionnaires concerning balance problems, walking aids and leg preferences were performed and it was noted whether subjects were able to stand freely on only one leg.

2.2. Experimental procedures

In the GVS experiment subjects stood bare-foot on a fixed platform. Lines were drawn on the force plate to define specific stance widths of either 20 cm between the middle of the feet or feet close together. In case of excessive sway or falling over, an assistant stood behind the subject for safety. For additional safety, there was a nearby frame the subject could hold if absolutely necessary. Subjects were studied with eyes open or closed, while standing with their feet together or apart, and standing either on solid ground or on a compliant surface (foam). Four specific combinations of these factors, called "sensory conditions" were applied in the present experiment:

- ots: **o**pen eyes, feet **t**ogether, standing on **s**olid ground
- cas: **c**losed eyes, feet **a**part, standing on **s**olid ground
- cts: **c**losed eyes, feet **t**ogether, standing on **s**olid ground
- caf: **c**losed eyes, feet **a**part, standing on **f**oam

In the most challenging condition subjects stood on a 5 cm thick rectangular piece of foam (Airex Balance-Pad, Alcan Airex AG, Switzerland) at their comfortable stance width (typically the feet were separated by about 20 cm). The experiment always began with an eyes open condition. The three subsequent conditions followed randomly. Finally, the four conditions were tested for a second time in randomised order. Since each condition was tested twice there was a maximum of 8 trials. Single trials from subjects who lost balance in the corresponding sensory conditions without being stimulated were omitted from further analysis.

The experimental setup is depicted in Fig. 1. To get stable GVS-elicited EMG responses in the soleus muscle and to induce a body sway in the anterior–posterior direction, the subject was asked to keep the head turned close to 90° toward the left side without pitching or tilting. In addition, the subject was told to minimize sway while leaning slightly forwards during the 3 min of one trial and to keep his arms relaxed hanging at the sides and with the hands not touching anything else other than the body since hand contact with a fixed object reduces the amplitude of GVS-elicited EMG responses (Britton et al., 1993).

2.3. Stimulation and recordings

Stimulation surface electrodes (Compex, 5 cm × 5 cm) were attached over each mastoid process so that there was one electrode behind each ear. With this configuration, stimulation occurs in a binaural bipolar manner. An elastic headband was wrapped around the head to hold the electrodes in place. Stimuli were generated through an isolated custom-made constant current stimulator. The stimulus consisted of either a positive (anode right) or negative (anode left) 3 mA rectangular, uniphasic direct current. Subjects were familiarised with the galvanic vestibular stimulation with a couple of preliminary stimuli where the stimulation current was slowly raised from 0 to 3 mA. In 2 of 16 subjects stimulation intensity was reduced to 2 (Subject 3) and 2.6 mA (Subject 14) due to discomfort of stimulation. Since there is no stimulus dependence of ML response latency between 2 and 4 mA (Ali et al., 2003), data of these subjects was included in the analysis. To avoid any overlap of the later parts of the EMG on-response with the