Neuroscience 244 (2013) 134–146

EFFECTS OF BODY TO HEAD ROTATION ON THE LABYRINTHINE RESPONSES OF RAT VESTIBULAR NEURONS

M. BARRESI,[a] C. GRASSO,[a] G. LI VOLSI[b] AND D. MANZONI[a]*

[a] *Department of Translational Research and New Technologies in Medicine and Surgery, University of Pisa, I-56127 Pisa, Italy*

[b] *Department of Biomedical Sciences, University of Catania, I-95125 Catania, Italy*

Abstract—Vestibulospinal reflexes elicited by head displacement in space depend on the direction of body displacement, because the neuronal responses to labyrinthine stimulation are tuned by neck displacement: a directional tuning takes place in the medial cerebellum and in spinal motoneurons, while a gain and a basal activity tuning can be observed in the reticular formation, a target structure of the medial cerebellum. In the present study, we investigated whether also the response of vestibular nuclear neurons (another target of the medial cerebellum) to labyrinthine stimulation is tuned by neck displacement and which parameters of the response are modulated by it. In urethane-anaesthetized Wistar rats, single-unit activity was recorded from the vestibular nuclei at rest and during wobble of the whole animal at 0.156 Hz. This stimulus tilted the animal's head by a constant amplitude (5°), in a direction rotating at a constant velocity over the horizontal plane, either in clockwise or counter clockwise direction. The gain and the direction of neuronal responses to wobble were evaluated through Fourier analysis, in the control position (with coincident head and body axes) and following a body-to-head rotation of 5–30° over the horizontal plane, in both directions. Most of the vestibular neurons modified their response gain and/or their basal activity following body-to-head rotation, as it occurs in the reticular formation. Only few neurons modified their response direction, as occurs in the cerebellum and in spinal motoneurons. The different behaviour of cerebellar neurons and of their vestibular and reticular target cells, suggests that the role played by the cerebellum in the neck tuning of vestibulospinal reflexes has to be reconsidered.

Key words: cerebellum, reticular formation, vestibular nuclei, vestibular reflexes, neck rotation.

INTRODUCTION

Vestibulospinal (VS) reflexes modify the postural tone according to head position in space (Von Holst and Mittelstaedt, 1950; Roberts, 1978). They are spatially organized, i.e. each muscle is maximally activated for a specific, ''preferred'' direction of head tilt (Wilson et al., 1986). Vestibular signals that monitor head displacement in space have to be integrated with proprioceptive neck signals related to the body-to-head position (von Holst and Mittelstaedt, 1950; Roberts, 1978), in order to elicit VS reflexes appropriate to stabilize the body position. It is well known that a linear interaction of VS and cervicospinal (CS) reflexes elicited by coplanar head and neck rotations (Lindsay et al., 1976; Ezure and Wilson, 1983; Manzoni et al., 1983), modulates the postural tone only when the position of the trunk in space changes. A similar interaction seems also to underline the perception of body motion in healthy humans (Mergner et al., 1991, 1997). In this study, however, we address another aspect of the interaction of neck and vestibular signals, which may take place when head and neck rotations are not coplanar (Mergner et al., 1997). Indeed, in order to maintain balance (Fig. 1A, B), an identical labyrinthine signal elicited by body sway (black arrows) must give rise to different postural responses (white arrows), if the head is kept in different static positions with respect to the body: in this instance, tonic neck input may allow to infer body motion from labyrinthine signal, leading to a change in the reference frame of the vestibular input from head to body. This is the reason why, during galvanic vestibular stimulation of the labyrinth, the direction of the perceived (Fitzpatrick et al., 1994) and the elicited (Lund and Broberg, 1983; Britton et al., 1993; Fitzpatrick et al., 1994) body sway changes along with the head-to-body position, in spite of the similar activation of vestibular afferents. There is an extensive literature on the neural mechanisms underlying the linear interaction of vestibular and neck reflexes elicited by co-planar head and neck rotations (Denoth et al., 1979; Boyle and Pompeiano, 1981; Kubin et al., 1981; Anastasopoulos and Mergner, 1982; Pompeiano et al., 1984; Wilson et al., 1984; Mergner et al., 1985; Kasper et al., 1988). In contrast, only few studies investigated how tonic neck input elicited by a sustained body-to-head displacement modifies the labyrinthine responses elicited by non coplanar animal tilts (Manzoni et al., 1998, 1999; Kleine et al., 2004; Shaikh et al., 2004). In particular, it has been shown that the preferred directions of the responses of the limb muscles to animal tilt rotate in the same

---

*Corresponding author. Address: Dipartimento Traslazionale, Università di Pisa, Via S. Zeno 31, 56127 Pisa, Italy. Tel: +39-50-2213466; fax: +39-50-2213527.

E-mail address: manzoni@dfb.unipi.it (D. Manzoni).

Abbreviations: CCW, counter clockwise; CW, clockwise; D, direction; S_{MAX}, maximal sensitivity vector; SN, signal-to-noise; SPDH, sequential pulse density histogram; SU, side-up; VS, vestibulospinal.

0306-4522/13 $36.00
http://dx.doi.org/10.1016/j.neuroscience.2013.04.010

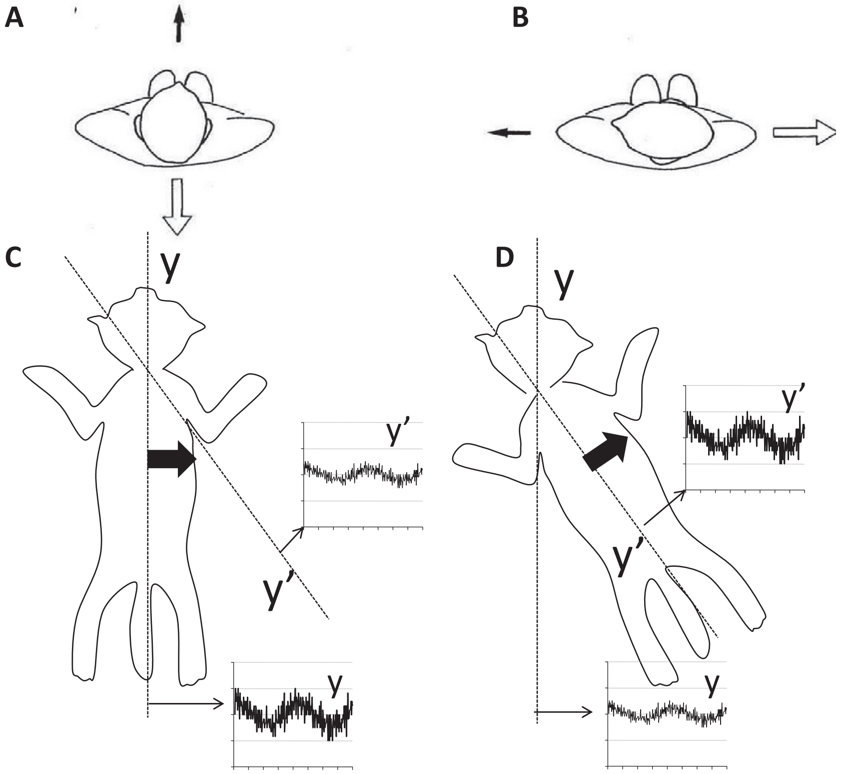

Fig. 1. Neck tuning of VS reflexes. (A) Subject swaying in the sagittal plane, in the direction of the black arrow. (B) Subject swaying in the frontal plane, in the direction of the black arrow. In both A and B, for opposing body sway, appropriate postural reaction have to be generated, pushing the body in the direction of the white arrows. Note that the direction of head displacement (and, as a consequence, the elicited vestibular input) is identical in A and B, but the postural responses must be differently oriented in order to maintain balance. This change in postural response can be achieved because the relative position of the head with respect to the body changes the coupling between the vestibular input elicited by body sway (black arrows) and the postural response (white arrows). (C) In the decerebrate cat, when the head and body longitudinal axes are aligned, the maximal EMG response to whole-body tilt (vestibulospinal reflex) of the forelimb extensor triceps brachii is obtained for a rotation in the frontal plane, around the longitudinal head–body axis (*y*), towards the side of muscle recording. The thick, black arrow represents the preferred response direction of this muscle. Tilt around an obliqual axis (*y*′) elicits a smaller EMG response. (D) Now the body is rotated with respect to the head, so that its axis coincides with *y*′. In this position, the maximal response is obtained for a whole-body tilt around the *y*′ axis, while the response to tilt around the *y* axis become smaller, so that the preferred response direction (thick, black arrow) remains perpendicular to the longitudinal body axis. The insets represent the modulations of EMG activity observed during tilt around *y* and *y*′. Note that the stimulation of vestibular receptors obtained by tilts around both *y* and *y*′ axes is the same in C and D, but, due to the differences in the tonic neck input, the pattern of vestibulospinal reflex has been modified.

direction and by the same amplitude as the body does, so that the pattern of muscle activity is related to the direction of body tilt, rather than head tilt (see Fig. 1C, D). The cerebellum plays a key role in this process, as in decerebrate cat (Manzoni et al., 1998) and in humans (Kammermeier et al., 2009) neck tuning of VS reflexes is abolished by inactivation or pathology of the cerebellar vermis. Within the cerebellar vermal cortex, in accordance with what is observed at motoneuronal level, body-to-head displacement modifies the preferred response directions of Purkinje (P-) cells, which rotate in the same direction and by the same amplitude as the body does (Manzoni et al., 1999). In a limited proportion of neurons gain modifications could be also observed. Further experiments were performed in the target structures of the medial cerebellar cortex, by using either tilting (Kleine et al., 2004) or linear accelerative (Shaikh et al., 2004) stimuli. In spite of the different methodologies, the outcome of these studies was that directional (but not gain) modifications are often elicited by changes in body-to-head position at the level of fastigial nucleus (Kleine et al., 2004; Shaikh et al., 2004), while they are only occasionally elicited within the rostral part of medial and lateral vestibular nuclei (Shaikh et al., 2004).

Since neck tuning of VS reflexes is abolished by cerebellar inactivation (Manzoni et al., 1998) or pathology (Kammermeier et al., 2009), a change in the relative body-to-head position could sequentially modify the directional properties of P-cell responses to the vestibular input, the responses of their target cells in the fastigial nucleus and of the reticulospinal and vestibulospinal neurons targeted by medial cerebellar structures. This succession of neural events may be responsible for the directional modifications observed at motoneuronal level.

This possible sequential processing has been recently challenged by the observation that, following neck rotation, neurons in the reticular formation often display gain and baseline firing rate changes (Barresi et al., 2012). This occurs only occasionally in the cerebellar