



## Tuning and sensitivity of the human vestibular system to low-frequency vibration

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### ABSTRACT

Mechanoreceptive hair-cells of the vertebrate inner ear have a remarkable sensitivity to displacement, whether excited by sound, whole-body acceleration or substrate-borne vibration. In response to seismic or substrate-borne vibration, thresholds for vestibular afferent fibre activation have been reported in anamniotes (fish and frogs) in the range  $-120$  to  $-90$  dB re 1 g. In this article, we demonstrate for the first time that the human vestibular system is also extremely sensitive to low-frequency and infrasound vibrations by making use of a new technique for measuring vestibular activation, via the vestibulo-ocular reflex (VOR). We found a highly tuned response to whole-head vibration in the transmastoid plane with a best frequency of about 100 Hz. At the best frequency we obtained VOR responses at intensities of less than  $-70$  dB re 1 g, which was 15 dB lower than the threshold of hearing for bone-conducted sound in humans at this frequency. Given the likely synaptic attenuation of the VOR pathway, human receptor sensitivity is probably an order of magnitude lower, thus approaching the seismic sensitivity of the frog ear. These results extend our knowledge of vibration-sensitivity of vestibular afferents but also are remarkable as they indicate that the seismic sensitivity of the human vestibular system exceeds that of the cochlea for low-frequencies.

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The otolith organs, the sacculus, utriculus and lagena, primarily respond to whole-body acceleration or tilt in gravity [9]. In fish these also are important auditory structures for acoustic near-field (particle motion) sensing [13,17]. Several studies have determined behavioral particle motion audiograms for non-specialist species of fish, e.g. the cod, plaice and dab [4]. These have indicated that the region of best sensitivity lies between 40 and 120 Hz, with threshold acceleration values of about  $-120$  dB re 1 g at 80 Hz. During the course of evolution the amniote ear developed new structures for far-field (sound pressure) hearing in air, including the basilar papilla and the mammalian cochlea [6].

It has been established, however, that the otolith organs in terrestrial vertebrates have conserved a particular sensitivity to substrate- or bone-conducted sound [2,15,16,22] consistent with their function as near-field sound sensors in fish [4]. In some species of frog the saccule shows a fish-like band-pass response to acceleration with best frequencies between 20 and 160 Hz and thresholds between  $-90$  and  $-120$  dB re 1 g, while others show a low-pass response with best frequencies at 10–20 Hz [14]. Sensitivity to audio-frequency vibration has also been demonstrated in mammalian vestibular organs. In the monkey [27] best frequencies were

between 125 and 177 Hz, with phase-locking threshold as low as  $-80$  dB re 1 g, and in the guinea-pig at 500 Hz thresholds were 10 dB above the ABR threshold [3]. At present, however, no such threshold measurements have been obtained for the human vestibular system and this was the aim of our study.

Non-invasive assessment of human vestibular sensitivity can be accomplished by measurement of the powerful vestibulo-ocular reflexes (VOR) to head acceleration. The VOR normally serves to maintain eye gaze with head tilt or rotation and its main effects are mediated by a simple three-neuron arc connecting the vestibular portion of the 8th nerve to the motor neurones of the extraocular muscles [1]. In response to stimuli such as head movements, reflex activity occurs in the extraocular muscles, producing a compensatory eye movement. By placing surface electrodes around the eyes, synchronous muscle activity can be recorded in the form of ocular vestibular evoked myogenic potentials (OVEMPs) [23,25]. These responses are vestibular, rather than cochlear, in origin as they are present in deaf patients but are absent in patients with loss of vestibular function [18,24]. We aimed to measure the tuning and sensitivity of OVEMPs to whole head vibration in the transmastoid plane.

Four volunteers (2 females and 2 males between 31 and 52 years of age) with no auditory or vestibular deficits were stimulated using sinusoidal accelerations between 12.5 and 800 Hz (12.5, 25, 50, 100, 200, 400 and 800 Hz). The subjects were seated

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