Original Paper

Mapping Sites on Bone and Soft Tissue of the Head, Neck and Thorax at Which a Bone Vibrator Elicits Auditory Sensation

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Key Words

Bone conduction • Soft tissue conduction • Mapping • Non-osseous bone conduction • Head • Neck • Thorax

Abstract

This study was designed to map the sites on the skin of the head, neck and thorax at which a clinical bone vibrator elicits auditory sensation. In 10 subjects with normal hearing, a bone vibrator delivering a 2000-Hz warble tone, at an intensity which was at least 5 dB below the intensity which elicited a sensation by air conduction over each site, was applied to 25 sites with an application force of 500 g. Auditory sensations were elicited at many soft tissue (underlying bone >1 cm below the skin) and osseous (bone <0.5 cm below the skin) sites on the head, neck and thorax in all subjects, down to the sternum and thoracic vertebrae. Therefore, auditory vibrations induced at many sites on the head, neck and thorax can reach the cochlea and elicit auditory sensation.

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Introduction

It has recently been shown that a clinical bone vibrator can elicit auditory sensation when it is applied not only over bone (e.g. mastoid), but also when it is applied over soft tissue. For example, auditory responses, either behavioral or auditory nerve and brainstem-evoked re-

sponses, are elicited when the vibrator is applied directly to the brain through a craniotomy [Freeman et al., 2000; Sohmer et al., 2000], or to the eye [Sohmer et al., 2000; Watanabe et al., 2008; Ito et al., 2011], to the cheek and neck [Adelman et al., 2012]; and auditory nerve and brainstem-evoked responses can be recorded in response to bone vibrator stimulation at the fontanelle in neonates [Sohmer et al., 2000]. This form of stimulation has been called ‘non-osseous’ bone conduction [Vento and Durrant, 2009]. However, soft tissue conduction (STC) is perhaps a more suitable term for this mode of stimulation. STC can interact with the other forms of auditory stimulation (air conduction, AC, and bone conduction, BC, at the mastoid) presented simultaneously to pairs of such sites, producing mutual pitch matching, mutual masking, beats at the difference frequency [Adelman et al., 2012] and mutual cancellation [Chordekar et al., 2011]. Taken together, these interactions between AC, BC (mastoid) and STC provide evidence that they all converge in the cochlea and that the mechanical mode of activation by STC in the cochlea is similar to that for AC and for BC (mastoid).

The present study was designed to map both the osseous sites on the skin over the skull, and the STC sites on the skin of the head, neck and thorax, defining the area over which the bone vibrator can elicit auditory sensation. Such a study can provide insight into the mechanism of soft tissue excitation of the cochlea and can perhaps contribute to the elucidation of the true nature of BC.

Methods

This study was conducted on 10 subjects (3 males, 7 females), aged 16–55 (mean 30) years. All subjects had normal pure tone AC and BC audiograms bilaterally, i.e. 15 dB HL or better. They were equipped with foam earplugs (Classic Superfit 30-2000 Aero Co, E-A-R) inserted deeply into both ears, throughout the entire procedure.

As a stimulus a warble tone at 2000 Hz was chosen because there is no occlusion effect [Tsai et al., 2005; Yacullo, 2009] and no tactile sensation at this frequency [Hyvarinen et al., 1968], so that the subjects could not perceive the vibratory stimuli when the bone vibrator was manually held or applied to the skin. The tone was generated by an AC40 clinical audiometer and delivered by means of a B71 standard clinical bone vibrator. The bone vibrator was applied to the different sites on the skin of the head, neck and thorax. In order to ensure a uniform standard application force at each site, a spring was attached to the surface of the bone vibrator opposite that in contact with the skin, and it was pressed down until the finger contacted a small rod at a point precalibrated as equal to an applied pressure of 500 g. In this way, the surface delivering the vibratory stimulation to the skin was pressed to the skin at each site with a force of 500 g. The vibrator was applied with a force of 500 g to each of the sites. In addition, at each site, AC thresholds were also determined with the bone vibrator also held over the site without touching it in order to ensure that the subject was not reporting responses to airborne sound produced by the vibrator.

Testing was initially performed at intensities (instrument settings in the BC mode of the audiometer) ranging from 25 to 50 dB HL, and always at least 5 dB below the intensity at which the subject heard the air-conducted component produced by the bone vibrator held in the air over each site. At sites at which no sensation was reported, stimulus intensity was increased until a sensation was reported, and then the bone vibrator was again held in the air over that site without touching the skin, in order to ensure that the sensation induced by the bone vibrator at that site was indeed BC or STC and not air conducted. At each region (head, neck, thorax), testing was terminated when bone vibrator-induced sound sensations could no longer be elicited at an intensity at least 5 dB below the intensity which elicited an air-conducted sound sensation when the bone vibrator was held in the air above that site. This

Fig. 1. Sites on the skin of the head, neck and thorax at which auditory sensations were elicited. **a** Front view. **b** Back view. Asterisks indicate the 'border' on the vertebral column for sensation in the 2 'extreme' subjects. Filled circles represent bone sites (underlying bone <0.5 cm below the skin). X represent STC sites (underlying bone >1 cm below the skin). Empty circles signify cartilage sites.

mapping protocol allowed examination of a maximal region on the head, neck and thorax, while at the same time avoiding contributions from air-conducted sound.

The bone vibrator was applied with the uniform application force of 500 g to about 25 points on the head, neck and thorax, along the midline coronal plane (anterior and posterior) and the right midsagittal plane, and at additional points: for example to the cheek (with the mouth wide open so that the vibrator had no contact with the teeth); to a neck site (at the submandibular triangle, i.e. the soft tissue below the jaw angle, below the earlobe); to a chin site (over the mylohyoid muscle, in the submental area), and points on a major neck muscle (sternocleidomastoid muscle).

The experimental protocol was reviewed and approved by the Hadassah Academic College Institutional Ethics Committee.

Results

The sites at which auditory sensation was reported are shown in figures 1 and 2. Figure 1a (front view), b (back view) and figure 2 (side view) show the sites at which sound sensation was elicited by applying the bone vibrator with uniform application force of 500 g at an intensity at least 5 dB below the intensity which elicited a sensation when the bone vibrator was

Fig. 2. A side view showing the sites on the skin with respect to the underlying skull bone. Filled circles mark bone sites (underlying bone <0.5 cm below the skin). X represent STC sites (underlying bone >1 cm below the skin). Empty circles mark cartilage sites.

held in the air (AC) over the site. The air-conducted thresholds in instrument settings in the BC mode of the audiometer at which the different subjects heard the airborne component of the sound when the vibrator was held over sites on the head and neck were 30–55 dB, while they were 55–70 dB (or no response at 70 dB) over sites below the neck on the thorax. The asterisks in figure 1 indicate the ‘border’ on the vertebral column beyond which sound sensation could not be elicited in the two ‘extreme’ subjects (subject with the smallest area over which sound sensation could be elicited and subject with the largest area) under these conditions. The subject with the largest area reported auditory sensation down to thoracic vertebra 12 posteriorly (T12), and anteriorly on the chest down to the lower sternum. In this subject, therefore, more than 25 sites were assessed. The posterior ‘border’ in the subject with the smallest area was at T2, and anteriorly at the mid-sternum. In both of these ‘extreme’ subjects, the ‘border’ 2 cm on either side of these midline (vertebra) sites was higher up on the chest and back. For example, in two of the subjects in whom the ‘border’ was at T2, laterally the ‘border’ was on the muscle (trapezius) at the level of the cervical vertebrae 6 and 7. In the subject with a ‘border’ at T12, the ‘border’ on soft tissue lateral to the midline vertebra site was at the level of T6 (on both the right and left side). The ‘borders’ in the other subjects were between those of the two ‘extreme’ subjects.

Filled circles in figures 1 and 2 represent skin sites at which the underlying bone could be estimated as being less than 0.5 cm below the skin (i.e. a maximal skin thickness of 0.5 cm, e.g. at the scalp, forehead and mastoid), and therefore were considered bony (osseous) sites. At the sites marked with X, the underlying bone was more than 1 cm below the skin, e.g. at the cheek, points on the sternocleidomastoid muscle, on the neck site (under the jaw angle below the earlobe) and under the chin. These represent soft tissue sites. Figure 2 can be used to provide an estimate of the distance between a skin site and the underlying bone. At the tip of the nose and at a site on the neck (over cartilage, marked with empty circles), sensation was reported only at higher intensities. As usual in this study, this was at intensities that were 5 dB below the intensity which was heard when the vibrator was in the air over that site.

Discussion

This study has clearly demonstrated that a standard clinical bone vibrator can elicit auditory sensation not only when it is applied to bony sites, but also to many soft tissue sites on the skin of the head, on the neck and even on the thorax (down to T12 posterior and lower sternum anterior in one subject, and T2 mid-sternum in another; in the other subjects the lower border for sensation was intermediate between these extremes). It is of course possible that had we used higher stimulus intensities, the area over which the vibrator could have induced auditory sensation would have been extended. However, higher intensities induced hearing through AC. Thus, the area for sensation reported here represents that induced by the intensity used, without contamination from AC.

The present mapping study was conducted with all of the necessary control procedures: the possibility that the subject reported auditory sensation due to AC sounds was prevented (the subject used deeply inserted ear plugs in both ears throughout the entire experimental procedure, and it was shown that there was no AC stimulation from the vibrator); tactile sensation from the vibrator was carefully controlled and prevented (there is no tactile sensation at this frequency [Hyvarinen et al., 1968]) so that the subject would not perceive the stimulus vibrations when the vibrator was applied to his skin; there was no occlusion effect as 2000 Hz were used; a uniform application force of about 500 g was used on all subjects at all sites.

As a result of the mapping protocol used in this study, the intensity applied to each site could not be taken as the actual threshold at each of the sites; in order to assess the largest possible area on the thorax, higher intensities were applied to sites further from the ear, as long as they were at least 5 dB below the intensity heard by the subject when the bone vibrator was held in the air above but not touching the skin at the site. Thus, the intensity applied to a site was not only determined by the threshold sensitivity of that site, but also by the distance between that site and the ear.

Although the pathway and mechanism enabling the vibrations induced on the skin of the neck and thorax to reach and activate the cochlea are not clear at this time, the experimental findings and additional available information help to rule out several possibilities. First of all, due to the anatomy involved, it is not likely that a major proportion of the vibrations induced in the superficial soft tissues of the neck (e.g. the chin, over the sternocleidomastoid muscle) and the thorax (e.g. the trapezius muscles) could be transmitted to the relatively distant skull bone. In addition, there is no direct bony contact between these sites and the skull bone; they are connected by several types of soft tissues (e.g. ligaments and spinal cord) and fluid (cerebrospinal fluid). Thus, it is not likely that the vibrations initiated at sites on the neck and thorax could lead to vibrations of the bony wall of the middle ear and the inner ear, inducing what were considered the 'classical' BC mechanisms of inner ear activation. The major routes of BC which have been suggested are based on inertia of the ossicular chain and of the cochlear fluids and cochlear compression-distortion [e.g. Tonndorf, 1968; Stenfelt and Goode, 2005], eventually leading to relative motion between the stapes footplate and the oval window, with bulk fluid volume displacements between the oval window and the round window, a pressure difference across the basilar membrane and a passive traveling wave.

Furthermore, in the presence of a large difference in acoustic impedance (defined as the product of the density of the media and the velocity of sound in that media) between two media, acoustic frequency vibrations induced in one of them would be reflected at the interface with the second [Wever and Lawrence, 1954]. Therefore, since the acoustic impedance of bone ($7.8 \times 10^6 \text{ kg/m}^2 \text{ s}$) is greater than that of water ($1.52 \times 10^6 \text{ kg/m}^2 \text{ s}$), most of the vibrations in the water would be reflected from the bone and not transmitted into it [Baun, 2004]. Nevertheless, the cochlea is activated during the soft tissue stimulation, and the sub-

jects report auditory sensation. Furthermore, the results of a recent animal study have demonstrated that the inner ear can be activated even when the entire ossicular chain, stapes footplate and round window have been immobilized (following appropriate surgery and application of glue), by applying a bone vibrator to a saline pool in the surgical area [Perez et al., 2011]. For all of these reasons, it is not likely that the soft tissue vibrations lead to vibrations of the stapes footplate in the oval window. Therefore, it seems that the auditory frequency vibrations induced by the bone vibrator on soft tissue sites somehow reach the inner ear in some way and activate it without relative motion between the stapes footplate and the oval window and therefore without bulk fluid displacements between the stapes footplate and the round window.

It is interesting to note, as pointed out in the introduction, that recent studies have shown that the three modes of auditory stimulation (AC, BC at the mastoid and STC) interact with each other in the cochlea, producing mutual pitch sensation, mutual masking, beats at the difference frequency [Adelman et al., 2012] and mutual cancellation [Chordekar et al., 2011]. Furthermore, such interactions in the cochlea also include a distortion product otoacoustic emission at $2f_1 - f_2$ which can be elicited with the f_1 presented by AC and f_2 at the ear (a soft tissue) [Watanabe et al., 2008; Ito et al., 2011]. All of these interactions between the three modes of stimulation take place even though, as explained above, stimulation at STC sites probably does not induce a passive traveling wave on the basilar membrane. This has interesting implications for the other modes of stimulation.

Evaluation of auditory sensation elicited from STC sites may be useful: it is possible that audiograms elicited from such soft tissue sites (in addition to standard AC and BC at the mastoid) can contribute to the clinical diagnosis in different types of hearing loss, and this should be evaluated in future studies.

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