Audiology & Neurotology

Published online: May 19, 2015

Audiol Neurotol 2015;20(suppl 1):44–47
DOI: 10.1159/000380747

How to Quantify Binaural Hearing in Patients with Unilateral Hearing Using Hearing Implants

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Key Words
Bilateral deafness · Binaural masking level difference test · Binaural summation · Conductive hearing loss · Head shadow effect · Localisation · Unilateral hearing

Abstract
Application of bilateral hearing devices in bilateral hearing loss and unilateral application in unilateral hearing loss (second ear with normal hearing) does not a priori lead to binaural hearing. An overview is presented on several measures of binaural benefits that have been used in patients with unilateral or bilateral deafness using one or two cochlear implants, respectively, and in patients with unilateral or bilateral conductive/mixed hearing loss using one or two percutaneous bone conduction implants (BCDs), respectively. Overall, according to this overview, the most significant and sensitive measure is the benefit in directional hearing. Measures using speech (viz. binaural summation, binaural squelch or use of the head shadow effect) showed minor benefits, except for patients with bilateral conductive/mixed hearing loss using two BCDs. Although less feasible in daily practise, the binaural masking level difference test seems to be a promising option in the assessment of binaural function.

Introduction

The present paper focuses on binaural hearing in patients with unilateral or bilateral hearing loss who use auditory implants. Cases of severe sensorineural hearing loss are treated with cochlear implants (CIs) and cases of conductive or mixed hearing loss receive implantable bone conduction devices (BCDs).

Binaural hearing refers to fused processing of bilateral auditory inputs [Mencher and Davis, 2006]. Therefore, the detection of interaural differences in loudness and in phase enables the localisation of sound sources (binaural processes), for example. Furthermore, speech recognition might be improved in an environment with multiple sound sources.

The importance of binaural hearing for daily functioning exceeds the primary auditory advantages. Recent evidence in favour of hearing with two competitive ears comes from research in children with one normal-hearing ear and a second severely hearing-impaired (unaided) ear. Studies have shown that such children might develop delays in educational achievements, for example, resulting in poor verbal cognition compared to non-verbal cognition [Lieu, 2013], even despite special training programmes [Lieu et al., 2012]. Similar results were found in studies comparing bilaterally deaf children listening with one hearing ear (unilateral CI) and with both ears (bilateral CIs). De Raeve [2014] showed that, in the long run, deaf children with bilateral devices had verbal-cognitive test scores close to normal and much better than unilaterally implanted children. This outcome proved to be mediated by hearing abilities (speech perception in noise or perception of soft sounds owing to binaural summation). It was concluded that better listening capacity enabled more effective 'incidental learning'; most knowledge that children acquire are not learned in structural educational settings, but rather 'incidentally' throughout the day. These studies indicate that hearing with two ears is essential for children to develop their full cognitive potential.

This paper addresses the problem of how to quantify the primary benefit (at the auditory level) of bilateral hearing in the clinic, and which tests are appropriate to study binaural hearing. Tests should be effective and feasible and have discriminative power. The most frequently applied tests to access binaural hearing in clinical studies are measurements of binaural summation and the effects of the acoustic head shadow (in principle physical factors), and two more measurements based on (sub)cortical processing, namely directional hearing and central unmasking (squelch effect).

Methods

The literature was reviewed with the help of very recently published, systematic reviews in the field of binaural hearing in patients using auditory implants (CIs or implantable BCDs). Our search comprised only those papers cited by the authors of the four systematic reviews.

With regard to the binaural hearing in patients with bilateral conductive or mixed hearing loss using unilateral versus bilateral percutaneous BCDs, the literature was reviewed by Janssen et al. [2012]. The authors compared bilateral with unilateral application. Danhauer et al. [2010] reviewed the literature on BCD treatment of unilateral, conductive hearing loss of congenital origin (with a second normal-hearing ear). Studies on unilateral versus bilateral cochlear implantation in bilaterally deaf subjects were reviewed recently by van Schoonhoven et al. [2013], and, even more recently, Vlastarakos et al. [2014] published a review on the CI use in patients with single-sided deafness and a second normal-hearing ear. We excluded the evaluation of CROS (contralateral routing of signals) devices as CROS stimulation does not introduce binaural cues in these patients.

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Table 1. Summary of outcomes from binaural tests reported in published systematic reviews (primarily for implanted adult subjects)

Review article	Device(s)	Subjects	Summation	Head shadow	Localisation[1]	Squelch
van Schoonhoven et al. [2013]	2 CIs	Bilaterally deaf	N.S.	N.S.	15–30°	N.S
Vlastarakos et al. [2014]	CI	Unilaterally deaf	N.S.	7 dB to N.S.	12–22°	1.9 dB to N.S.
Janssen et al. [2012]	2 BCDs	Bilaterally deaf, CHL	4.0–5.4 dB	2.5–3.1 dB	35°	N.S.
Danhauer et al. [2010]	BCD	Unilaterally deaf, CHL	N.S.	1.2 dB to N.S.	6°	N.S.

CHL = Conductive hearing loss; N.S. = not significant. [1] Improvement in azimuth (°).

Outcome: Binaural Summation

Listening with two ears instead of one results in better hearing of 4–6 dB and is referred to as binaural summation [Mencher and Davis, 2006]. Consequently, in contrast to unilateral hearing, listening with two ears leads to an improvement of approximately 5 dB in hearing thresholds. This directly affects recognition of soft speech. Mostly, binaural summation is assessed by measuring the speech recognition threshold, which is obtained when listening with two versus one ear.

The assumption is that the two ears have similar capacities in terms of speech processing. In an ear with congenital hearing loss/deafness or a sound-deprived ear owing to a long-standing hearing loss/deafness, poor processing of speech might lead to a non-optimal binaural summation score. Table 1 shows the summary of outcomes of binaural tests reported in the above-mentioned systematic reviews. The numerical data included in the reviews are used if available; otherwise, the specific values were obtained from the original papers. In table 1, the data in column 4 present the derived binaural summation scores; additionally, if significant scores were present according to the authors of the four reviews, ranges are also presented. It should be noted that binaural summation is a relative measure (difference in outcomes between two measurement conditions); therefore, the speech material used is of little influence, thus enabling comparisons across studies.

Binaural summation is less than the reference value of 4–6 dB, indicating that the ears do not interact adequately; a score within the normal range is only found for the patients with bilateral conductive/mixed hearing loss provided with bilateral BCDs. However, for bilateral BCDs, theoretically, the lower than expected binaural summation of 6 dB might be attributed at least in part to interference of the bilaterally induced vibrations of the skull [Deas et al., 2010].

In conclusion, binaural summation is not a convincing measure of binaural benefit especially in CI users. Nonetheless, improvements in binaural summation scores over time have been reported, with a time scale of years [van Schoonhoven et al., 2013; Vlastarakos et al., 2014]. This suggests that binaural summation may be considered a good measure of binaural hearing particularly for CI patients longitudinally.

Outcome: Speech Recognition in Noise with Spatially Separated Speech and Noise Sources

If speech and noise are presented by a speaker in front of the patient and, next, the noise is presented at the right side, normal listeners will perceive the speech much better. In the latter condition, the subject can use the left ear that is in the acoustic head shadow for the noise. Furthermore, while the speech is perceived in phase by the two ears, after moving the noise source, the noise signal is no longer perceived in phase (especially not in the low frequencies) because of different travelling times (interaural time delay). This latter cue is used for localisation and in this experimental condition, it leads to a perceptual separation of speech and noise sources and, therefore, to reduced masking of the speech by the noise. This phenomenon is referred to as the squelch effect.

The head shadow effect is a monaural effect that does not require any subcortical processing, except that the patient should be able to listen with the ear with the better signal-to-noise ratio and ignore the input to the other ear. Depending on the speech material and noise used, effective use of the head shadow will have a positive effect of typically 3–5 dB in the speech recognition threshold [Agterberg et al., 2011]. It should be noted that the head shadow and squelch effects are relative measures (difference between two measurements); therefore, the speech material used is of little influence, thus enabling comparisons over studies.

In table 1, column 5 shows obvious differences within and between groups in the effective use of the head shadow, suggesting that only some patients are able to exclusively select the ear with the better speech-tonoise ratio for listening. Especially the CI users and the BCD users with unilateral conductive hearing loss do not benefit.

Binaural squelch is based on subcortical processing of the two inputs and, thus, a true binaural measure. Numerically, the squelch effect measured with speech in noise (i.e. broadband signals) is marginal, typically in the order of 1- to 2-dB improvements in the speech recognition threshold, and is often hard to assess as a consequence [Agterberg et al., 2011]. Column 7 (table 1) presents squelch data for the patient groups. Indeed, low or non-significant values are reported.

A simplified, more effective way to measure squelch is the binaural masking level difference (BMLD). In this test, low-frequency tones are used instead of (broadband) speech. First of all, a test tone and noise (narrow-band noise having the same central frequency as the frequency of the test tone) are presented to the two ears in phase. Next, the phase of the tone is reversed in one ear only, which makes detection of the tone much easier. For low frequencies (250–1,000 Hz), the threshold for the tone in the noise might improve by 5–15 dB by reversing the phase of the tone in one ear. Instead of reversing the phase of the tone, the phase of the noise can also be reversed in one ear, leading to a similar result.

Concerning BCDs, there has been a debate on whether the BMLD outcomes are influenced by cross stimulation. Owing to the limited attenuation of acoustic waves in the skull bone, not only the cochlea ipsilateral to the implant is stimulated but also the con-

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tralateral cochlea, although to a somewhat lesser extent (between 0 and 15 dB attenuation [Stenfelt, 2005]). It has been suggested that addition of in- or out-of-phase signals at the ipsi- and contralateral cochlear level might affect the BMLD outcome [Bosman et al., 2001; AlOmari, 2014]. Recent work has shown that the effect of interference at the cochlear level is of minor influence; therefore, measured BMLDs can be ascribed mainly to binaural processing of bilateral inputs. Studying bilateral implantable BCDs, Bosman et al. [2001] reported mean BMLDs from 6 to 7 dB in the frequency range of 250–500 Hz and approximately 4 dB at 1 kHz. AlOmari [2014] observed similar results.

Concerning patients with bilateral CIs, BMLD measurements have been carried out using similar stimuli presented to a preselected electrode by direct stimulation (i.e. not via the audio processor) [Long et al., 2006; Van Deun et al., 2009; Lu et al., 2010]. Relatively consistent values have been reported, ranging from 4.6 to 9 dB for a test tone of 125 Hz. Hence, BMLD measurements can be considered a robust assessment of binaural hearing.

In conclusion, the effective use of the head shadow is not a general finding, especially not in the two CI groups reported. Binaural squelch using speech stimuli in noise is not a robust measure but rather a marginal effect, while the BMLD test seems to be the most robust, at least up to 1 kHz. However, the BMLD test must be performed using direct inputs of the hearing devices and requires special equipment. To date, standard procedures have yet to be developed to measure BMLDs in the sound field with the patient's own sound processor(s). Furthermore, tailoring of the BMLD measurement procedures is needed for use, especially in patients with unilateral hearing loss/deafness.

Outcome: Directional Hearing in the Horizontal Plane

Directional hearing in the horizontal plane is based on a direct comparison of the input to the two ears. The two most important cues that are used for directional hearing are interaural difference in loudness and interaural difference in arrival times of the stimulus to each ear [Blauert, 1997]. It should be highlighted that the interaural level difference cues are affected by differences in the compression behaviour of the device(s) and interaural time difference cues by processing time of the sound processor(s) used with implantable devices. As a consequence, directional hearing ability in the aided listening condition may be worse than in the unaided condition for an individual (i.e. assuming that the sounds are audible in the unaided condition). Especially when the second ear is a normal-hearing ear, such sound processor characteristics might impact directional hearing. An additional problem in today's sophisticated hearing devices is that often (adaptive) directional microphones are utilised, which have been proven to be beneficial for speech recognition in noise, but directional microphones jeopardise directional hearing.

Another inevitable problem, especially when using BCDs in conductive/mixed hearing loss, is cross stimulation, owing to the limited attenuation of acoustic waves in the skull bone [Stenfelt, 2005]. Nevertheless, improved directional hearing has been found in users with bilateral hearing loss when changing from unilateral to bilateral BCDs, although the scores were obviously poorer than those of normal-hearing subjects [Bosman et al., 2001]. In table 1, the data in column 6 reflect the beneficial effect on the localisation error (listening with two vs. one ear) in degrees (root mean square values). Indeed, the group of bilateral BCD users improved most; in contrast, patients with unilateral conductive hearing loss using a BCD showed little benefit. In either group of CI users, a rather consistent benefit in the order of 15–30° was seen.

Several patients with unilateral hearing, especially those with congenital onset, develop some directional hearing, based on monaural cues. It has been demonstrated that they can use monaural cues effectively (like acoustic head shadow and spectral pinna cues [Agterberg et al., 2012]). This might have caused the observed, small benefit in localisation with BCD treatment, because the unexpected good, unaided scores were within the range of the aided scores, suggesting poor benefit (table 1) [Agterberg et al., 2011].

In conclusion, the data in table 1 show that directional hearing seems to be the most effective measure to quantify binaural hearing. As stated above, it is a real binaural measure based on effective processing of the two incoming signals. To minimise the use of pinna reflexions and head shadow as monaural cues, it is advised to apply a 4-kHz cut-off frequency for broadband signals and to rove the amplitude (e.g. ±6 dB in 6-dB steps). Short-duration signals should be used, preferably <0.3 s. This will minimise the effect of head movements and prevent adaptive systems from becoming activated (e.g. noise reduction algorithms and adaptive directional microphone settings). It should be emphasised that part of the variation in results between studies is caused by different set-ups (number of speakers and their locations, number of presentations, type and length of stimuli or room acoustics). The intra-subject standard deviation (repeated measurements) should be determined to judge whether a change in outcome is statistically significant or not.

Disclosure Statement

The authors report no conflict of interest.

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