

Acoustic and Perceptual Effects of Signal Delay in Open-ear Fittings

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In open-ear fittings, the amplified signal is delayed relative to the direct air-conducted signal and the bone-conducted signal for the listener's own voice, affecting sound quality.

This study found that venting differences (occluded vs vented vs open ear) had a greater effect on sound quality than delays in the range 3 to 20 milliseconds.

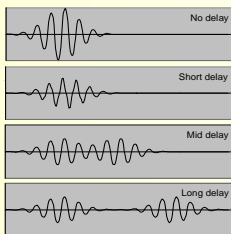
The speed of sound in air is about 330 metres per second. This means that sound takes a finite time to travel from one place to another. This leads to time delays between the production of a sound and its arrival at the listener's ear.

Delay	Cause of delay
50 μ s	Time for sound to travel from front port to back port of a directional microphone
200 μ s	Time for sound to travel from the output to the input of a BTE hearing aid via the feedback path
700 μ s	Time for sound to travel from vocal folds to the ear by air conduction
6 ms	Time for sound to travel between two people talking 2 m apart
8 ms	Digital signal processing delay for a 64-band FFT at 16 kHz
250 ms	Reverberation time of a typical room

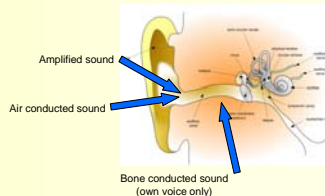
An additional time delay can be introduced by the digital signal processing in hearing aids, such as the 8 ms FFT delay in the table above. Typical hearing aid delays range from 1 to 15 milliseconds.

A delay is not detectable by the listener unless they have a (non-delayed) reference point. The reference point may be visual as in lipreading, or tactile as in hitting a table tennis ball, but usually, the reference point is the unamplified sound itself.

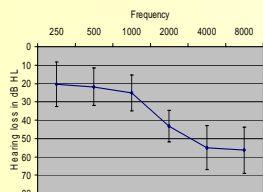
Sound quality is affected when a delayed copy of a sound is added to the original. The effect depends on the length of the delay. A zero delay just doubles the amplitude and makes the sound louder. A short delay changes the waveform and spectrum of the sound, a long delay gives rise to an echo, and intermediate delays may be perceived as reverberation.



When a person wearing an open-fit hearing aid is talking, three sounds add together in the ear canal: the bone conducted sound which has a very short delay; the air-conducted sound which has about 700 ms delay; and the amplified sound which has a longer delay because of the signal processing time in the hearing aid.



In a conventional hearing aid, the unamplified air-conducted sound is attenuated by the earmold.



Average hearing loss \pm one standard deviation

The hearing aids were fitted optimally to the listener's audiogram and preferences under each condition in a single test session, using the Configure™ software. Little change was required to the fittings when delay was changed under the same venting condition. More substantial changes were required when the venting was changed.

Sound quality ratings were obtained from each listener in 12 conditions (four delays X three venting conditions) while listening to their own voice through the hearing aids. A seven point "Likert rating scale" was used in conjunction with four statements about sound quality. A Likert rating scale uses numbers to indicate the degree of agreement or disagreement with each statement:

1=strongly agree 4=neither agree nor disagree 7=strongly disagree.

The four statements for which the Likert scale was applied were:

- This speech sounds natural
- This speech sounds hollow
- I like the quality of this speech
- I can hear an echo

Wide Dynamic Range Optimization

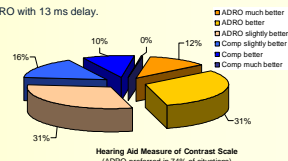
ADRO processing is the first wide dynamic range optimization amplifier for hearing aids and cochlear implants, used in the Cochlear Freedom™ and Sprint™ sound processors, the Bionic™ hearing aid range from Interton, and others. The ADRO amplifier uses statistical analysis of the output signal and fuzzy logic rules to keep sounds at a comfortable and audible level while maximizing the information available to the listener in every frequency band. It adapts automatically to all sound environments and maintains high quality sound in all conditions. The first blind trial of ADRO in BTE hearing aids for 19 subjects in 2002, resulted in high preferences for ADRO compared to WDRC. Further scientific clinical studies have consistently shown that ADRO simultaneously improves audibility and comfort and speech intelligibility in noise compared to WDRC without compromising sound quality (Blamey et al. JAAA 2004; Blamey, Trends in Amplification, 2005).

The initial clinical trial data were collected using 64-channel ADRO with 13 ms delay.

There are now multiple versions of ADRO

with different numbers of channels and very short processing time delays (including < 1ms).

A recent study by Mispagel and Valente (in press) compared 64-channel ADRO (13 ms delay) with 32-channel ADRO (6.5 ms delay). They found a slight difference in sound quality for two sounds (flute and running water), in favour of the 64-channel version with the longer delay.



STUDY DESIGN (Part 1)

Listeners with impaired hearing

The combined effects of delay and amplitude differences were investigated in a study of 11 listeners with mild-to-moderate sloping hearing loss.

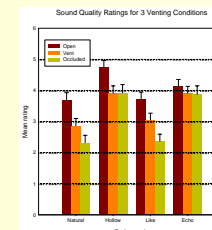
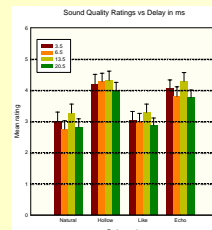
They were fitted binaurally with 16-channel ADRO® behind-the-ear hearing aids with controllable delay of 3.5, 6.5, 12.5, or 20.5 ms. The hearing aids used were Interton Bionic with specially modified DSP software.

Three venting conditions were compared in the study:

1. Occluded, with a standard earmold;
2. A standard earmold with a 2 mm vent; and
3. Open-fitting using Oticon comfort tip attached to the eartook of the hearing aid.

RESULTS (Part 1) Listeners with impaired hearing

The sound quality ratings for the listeners with impaired hearing are shown in the figures below, averaged over subject, for each delay and for each venting condition. Higher bars indicate better sound quality for each rating scale (i.e. more natural, less hollow, liked more, and less echo). Error bars show one standard error of the mean. Repeated measures ANOVA indicated no significant difference between the four delays for the hearing impaired subjects. The open fitting produced sound quality ratings that were significantly more natural, less hollow, and liked more than the other venting conditions ($p < 0.001$).



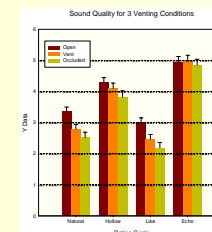
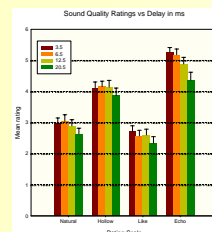
STUDY DESIGN (Part 2) Listeners with normal hearing

Recordings of the utterances of three speakers were made using probe tube microphones under the same 12 conditions as were used in the first part of the study (four delays X three venting conditions). The three speakers included two of the participants with impaired hearing from the first part of the study, wearing their individually fitted hearing aids. The third speaker had normal hearing and was fitted with ADRO hearing aids suitable for a person with a flat 40 dB HL hearing loss.

Nine normally hearing subjects listened to each recording four times in a random order, and used the same Likert Rating Scales for sound quality.

RESULTS (Part 2) Listeners with normal hearing

The sound quality ratings for the listeners with normal hearing are shown in the two figures below, averaged over subject and recording, for each delay and for each venting condition. Higher bars indicate better sound quality for each rating scale (i.e. more natural, less hollow, liked more, and less echo). Error bars show one standard error of the mean. Repeated measures ANOVA indicated no significant difference between the four delays for the normally-hearing subjects, except for the echo ratings, where there was significantly more echo for the 20.5 ms delay conditions ($p < 0.001$). As for the listeners with impaired hearing, the open fitting produced sound quality ratings that were significantly more natural ($p < 0.001$), less hollow ($p < 0.05$), and liked more ($p < 0.001$) than the other venting conditions.



The study led to five main conclusions:

- Venting had a strong effect on sound quality with both normal and impaired hearing
- Open-ear fittings were preferred and had a more natural sound, as well as greater physical comfort
- Delays up to 20 ms had no consistent effect on sound quality for untrained listeners with impaired hearing
- A delay of 20 ms was perceived as a slight echo by untrained listeners with normal hearing
- It may be misleading to base hearing aid designs on results for listeners with normal hearing