

# Open Versus Closed Hearing-Aid Fittings: A Literature Review of Both Fitting Approaches

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## Abstract

One of the main issues in hearing-aid fittings is the abnormal perception of the user's own voice as too loud, "boomy," or "hollow." This phenomenon known as the occlusion effect can be reduced by large vents in the earmolds or by open-fit hearing aids. This review provides an overview of publications related to open and closed hearing-aid fittings. First, the occlusion effect and its consequences for perception while using hearing aids are described. Then, the advantages and disadvantages of open compared with closed fittings and their impact on the fitting process are addressed. The advantages include less occlusion, improved own-voice perception and sound quality, and increased localization performance. The disadvantages associated with open-fit hearing aids include reduced benefits of directional microphones and noise reduction, as well as less compression and less available gain before feedback. The final part of this review addresses the need for new approaches to combine the advantages of open and closed hearing-aid fittings.

## Keywords

hearing aid, occlusion, earmold, open fit, real-ear measurements

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## Introduction

A hearing loss leads, among other deficits, to reduced audibility, a smaller dynamic range, and poorer speech recognition (Dillon, 2012). Consequently, people with a hearing impairment suffer from several disabilities that hamper conversations in everyday social life. Hearing aids can facilitate speech recognition and improve the quality of life (e.g., Dillon, 2012; Kochkin, 2011). They can be classified into two groups: Behind-The-Ear (BTE) and In-The-Ear (ITE) hearing aids.

The sound from the hearing aids needs to be delivered into the ear canal. This is achieved in a BTE via a custom-made earmold, foam tip, or silicone dome. The earmold is an individually manufactured part, which, may occlude the ear canal or may include a vent, that is, a second channel for air and sound exchange between the outside world and the ear canal. Dillon (2012) described the ear fitting as open, occluded, or as anywhere in between. Occluded fittings have no vents, but the leakage path due to imprecise fit of the earmold or dome can cause sound to pass into or out of the ear canal. Audiological characteristics as well as issues concerning cosmetic aspects, chewing sounds, secure retention, and the

perception of the user's own voice should be considered when choosing the earmold and the size of the vent (e.g., Dillon, 2012; Voogdt, 2005). Reported reasons for not wearing hearing aids include poor comfort and poor sound quality (e.g., Kiessling, Brenner, Jespersen, Groth, & Jensen, 2005; Kochkin, 2000). In the past, BTEs with occluding earmolds or small vents were often used, frequently resulting in increased sound levels in the ear canal at low frequencies when the user spoke and in complaints about the abnormal perception of the sound of their own voice as too loud, "boomy," or "hollow." This is called the occlusion effect (e.g., Dillon, 2012). The occlusion effect is especially prominent for listeners with normal hearing or with a mild hearing loss at lower frequencies (e.g., Carle, Laugesen, & Nielsen, 2002; Dillon, 2012; Kiessling et al., 2005).

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The perception of the user's own voice is often improved by increasing the diameter of the vent (Dillon, 2012), or by opening the ear canal using systems known as open-fit hearing aids, open-canal fittings, or open fittings. Mueller (2006) estimated that 40% of the BTEs fitted in the United States were open fit. This market share has increased since then. Reasons for the high-market share of open-fit hearing aids are reduced occlusion, improved comfort, improved cosmetics, higher customer satisfaction, and instant fit (e.g., Gnewikow & Moss, 2006; Johnson, 2006; Kuk, Keenan, Sonne, & Ludvigsen, 2005b; Mueller, 2006; Mueller & Ricketts, 2006; Otto, 2005; Taylor, 2006). This review addresses the occlusion effect, the different open-fit definitions, open-fit hearing aids, their objectives and limitations in comparison to closed-fit hearing aids, and the audiological and clinical implications of the outcomes.

## The Occlusion Effect

The ear canal consists of the cartilaginous and the bony canal. The cartilaginous canal covers the first third of the ear canal, beginning with the external entrance. It contains glands secreting cerumen, which has an antibacterial and antifungal effect. The other two thirds of the ear canal toward the tympanic membrane is the bony canal. The skin of the bony canal is very thin and sensitive. The ear canal typically exhibits two bends, the first bend being located at or near the entrance of the ear canal. The second bend is located at the transition from the cartilaginous to the bony sections (Dillon, 2012). Sound passes through the external ear canal, including the cartilaginous and bony ear canal, and is transmitted via the tympanic membrane to the middle and inner ear. Self-produced sound is not only transmitted via this air conduction pathway but also via bone vibrations through the skull. If the walls of the ear canal move relative to each other, which is the case for the cartilaginous canal for jaw vibrations and for vibrations of the temporal bone, these vibrations are transmitted into the ear canal (Dillon, 2012). If the ear canal is open, the vibrations can "escape" to the outside world. Closed earmolds block this "escape" path. As a result, the sound produced by bone conduction is retained in the ear canal and leads to the occlusion effect (e.g., Dillon, 2012; Mueller, 1994; Zwislocki, 1953). Opening the earmold, for example, with a vent, allows leakage of sound out of the ear canal and at least partly overcomes the difficulties caused by this occlusion. The bony canal does not contribute to the vibrations within the occluded ear canal. Therefore, another possibility for reducing the occlusion effect is to use an earmold that fills the whole cartilaginous canal (Dillon, 2012) or a sealed dome situated in the bony part of the canal.

## Quantifying the Occlusion Effect

The amount of occlusion can be quantified by objective measurements and subjective descriptions, called in this review objective and subjective occlusion effects, respectively. Dillon (2012) defined the objective occlusion effect as the increase in sound pressure level at low frequencies when closing the ear canal with an inactive hearing aid, as compared with the open ear canal, while the hearing-aid user speaks. The subjective occlusion effect can be described as the change in perception of one's own voice when wearing the hearing aid, for example, its "hollowness" or "boomyness." Paired comparisons (Bramsløw, 2010) or questionnaires (e.g., Gnewikow & Moss, 2006; Kiessling, Margolf-Hackl, Geller, & Olsen, 2003; Kuk et al., 2005b; Smith, Mack, & Davis, 2008; Taylor, 2006) have been used to assess this perception.

## The Objective Occlusion Effect

Objective measurements of the frequency response in the individual ear canal, so-called real-ear measurements (REM), are routinely conducted using probe microphones with and without the hearing aid in place while presenting external sounds (e.g., broadband noise or speech signals; for a detailed description, see Dillon, 2012) and without any utterances by the hearing-aid user. The measurement without the hearing aid provides the real-ear unaided response (REUR) or (after subtraction of the input level) the real-ear unaided gain (REUG). The REUG reflects the resonance of the ear canal, which leads to additional gain at frequencies around 2 to 3 kHz.

An earmold changes the acoustic properties of the outer ear and of the ear canal and reduces the REUG. The measurement with earmold and inactive hearing aid provides the real-ear occluded response (REOR) or, after subtraction of the input level, the real-ear occluded gain (REOG). The REOG reflects the direct transmission of sound via the vent into the ear canal. The transmission via the earmold's vent is determined by its Helmholtz resonance frequency, which depends on the residual ear canal volume and the vent diameter and length. At frequencies above the Helmholtz resonance frequency, the transmission of sound through the vent toward the tympanic membrane is increasingly attenuated (Dillon, 2012). The REOR and REOG should not be confused with the REAR (real-ear aided response) or REAG (real-ear aided gain) that are determined with an active hearing aid and, therefore, describe the frequency response or (after subtraction of the input level) the amplification produced by the hearing aid. With increasing vent size, the REOG is shifted more and more toward the REUG and, for open hearing aids, the REOG and the REUG are similar.

REM can also be used to quantify the objective occlusion using self-vocalization instead of external sounds. For measurements of the REUR and the REOR conducted while the hearing-aid user vocalizes a sound, for example, /i/ (e.g., Kuk et al., 2005b, Kuk, Keenan, & Lau, 2009), the abbreviations are changed to  $REUR_{VOC}$  and  $REOR_{VOC}$ , respectively. The difference between those two measures ( $REOR_{VOC} - REUR_{VOC}$ ) gives the increase in level at low frequencies and the decrease at high frequencies when occluding the ear canal with an earmold and, therefore, provides a measure of the objective occlusion effect. Kuk and Keenan (2006) described a reduction in low-frequency level by 4 dB for each increase in vent diameter by 1 mm.

### The Subjective Occlusion Effect

Individual listeners describe the level increase at lower frequencies due to the occlusion effect as making their own voice sound unnatural, like “talking in a barrel,” too loud, “boomy,” or “hollow” (e.g., Dillon, 2012; Jespersen, Groth, Kiessling, Brenner, & Jensen, 2006; Kiessling et al., 2005). Those descriptions or ratings are called the “subjective occlusion effect.” The subjective perception is significantly improved, as compared with a closed earmold, when a vent with a diameter of 1 mm is included or when this diameter is increased from 1 to 2 mm (Kuk, Keenan, & Lau, 2005a; Kuk & Keenan, 2006). Dillon (2012) regarded a vent size of 2 mm “as a good starting point for fixing the occlusion problem”. However, open fittings or an additional increase of the vent size are often necessary to further reduce or eliminate the subjective occlusion effect (e.g., Fulton & Martin, 2006; Kiessling et al., 2005; Kuk et al., 2005a; Kuk et al., 2009; MacKenzie, 2006).

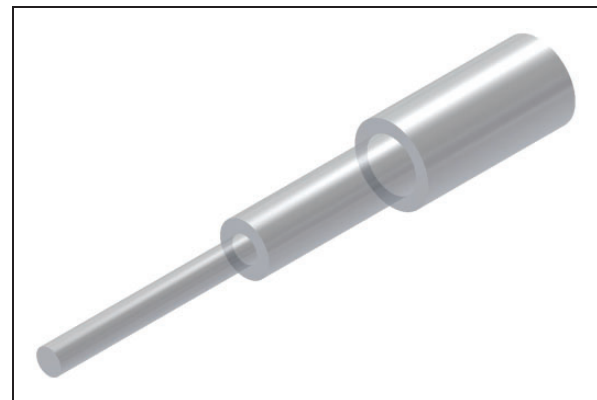
Although the subjective occlusion effect correlates with the objective occlusion effect, individual subjective ratings manifest a broad scatter (Kuk et al., 2005a). The subjective ratings may be influenced by loudness. Keidser, Katsch, Dillon, and Grant (2000) asked normal-hearing listeners to adjust the level of octave-filtered babble noise at 500 Hz and at 3 kHz to give the same loudness as a reference sound (1.5 kHz octave-filtered babble noise). This was done for open ears with free-field loudspeaker presentation and for occluded ears using the receiver in hearing aids. The results of this loudness balancing test were similar for the open and the closed conditions for noise centered at 3 kHz. However, for noise with a center frequency at 500 Hz, there was a difference of 5 to 15 dB between the open and occluded ears. On average, the measured level at the tympanic membrane for equal loudness was 10 dB higher in the closed condition than in the open condition. Despite considering several factors (e.g., transmission to the middle ear, bone conduction, mechanical vibrations), no physical explanation for the differences could be given.

Beside the occlusion effect, other measures that affect the subjective perception of the user’s own voice were examined by Jensen, Maas, Nielsen, Laugesen, and Flynn (2006) and Laugesen, Jensen, Maas, and Nielsen (2011). They examined factors such as the ability of a user to appropriately adjust the level of their own voice following and interacting in discussions, whispered communication, sound quality, and emotional consequences and concluded that hearing aid users rate their own voice differently than do normal-hearing persons, even if occlusion can be neglected.

### The Acoustic Mass

The ability of a vent to transmit sound is determined by its air column’s inertia, described by the acoustic mass. The amount of occlusion decreases with decreasing acoustic mass of the vent (Curran, 2012; Kiessling et al., 2005; Kuk et al., 2005a, 2009; Kuk & Keenan, 2006). The acoustic mass increases in proportion to both increasing length and the square of the decreasing diameter of the vent (Dillon, 2012). Hence, the occlusion effect can be reduced by shortening the length of the vent or by increasing the vent diameter. Leakage effects caused by, for example, loose fit earmolds are typically not included in the calculation of the acoustic mass (e.g., Jespersen et al., 2006; Kiessling et al., 2005; Kuk et al., 2005a).

Kuk et al. (2005a) measured the objective occlusion effect via REM with self-vocalized sounds. The occlusion effect was measured for different vent diameters in a custom-made, completely-in-the-canal (CIC) hearing aid. The vent length was divided into three sections. For each section, the diameters ranged from no vent up to 3 mm. For example, the first section might have a diameter of 1 mm, the second a diameter of 2 mm, and the third a diameter of 3 mm (see Figure 1). Without a vent, the measured average objective occlusion effect at

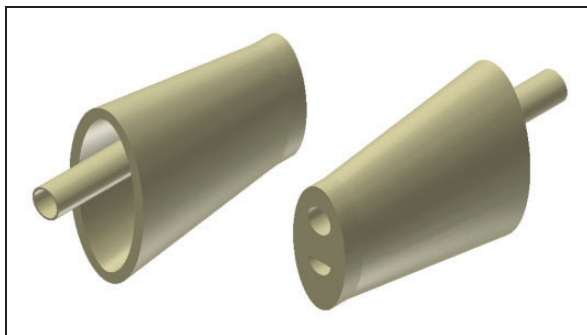


**Figure 1.** Sketch of an example of a vent configuration from Kuk et al. (2005a).

300 Hz ranged from 5 dB (for the 3 mm vent) to 17 dB. Kuk et al. (2005a) also calculated the acoustic mass of the different configurations. The correlation between the objective occlusion effect and the acoustic mass was significant ( $r=0.79$  as calculated from the given value  $r^2=0.62$ ). Kuk et al. (2005a) also analyzed the relationship between the middle ear compliance and the occlusion effect for the different vent diameters. They found a significant correlation ( $r=0.59$ ) only for the closed condition. Participants also judged the hollowness of their own voice by articulating “Baby Jeannie is teeny tiny.” The results showed a wide range of individual judgments on a scale between “very natural (10)” and “extremely hollow (1).” For example, a subjective rating of “2” was given for objective occlusion effects ranging from 1 to 21 dB. For higher ratings (9 to 10), the range was significantly smaller (6 to 10 dB). Nevertheless, the correlations between the objective occlusion effect and subjective ratings ( $r=-0.46$ ), as well as between the subjective rating and acoustic mass ( $r=-0.33$ ), were significant. Kuk et al. (2005a) concluded that the occlusion effect is related to the acoustic mass of the vent, which can be calculated from its length and diameter. Different diameters throughout the vent contribute to the acoustic mass according to their respective length. Therefore, from a theoretical point of view, it does not matter at which end (toward the tympanic membrane or toward the outside) vents are widened to reduce the occlusion effect.

### Alternative Vent Types

In the past, specific vent constructions were devised and evaluated in attempts to overcome the occlusion effect. Kiessling et al. (2005) evaluated objective occlusion for normal-hearing and hearing-impaired listeners using conventional custom made earmolds and “Flex-Vent™” earmolds (Jespersen & Groth, 2004; see Figure 2) connected to a BTE. The FlexVent™ earmolds had hollow acrylic shells with a changeable vent insert of 1 mm length. The cross-sectional area of the vent was equivalent to a



**Figure 2.** Sketch of a “Flex-Vent™”. Medial view (left) and lateral view (right).

circular vent with a diameter of 1.6 mm or 2.4 mm. These diameters were used for the conventional custom-made earmolds. The shorter vent of the FlexVent™ earmolds caused a reduced acoustic mass compared with the conventional earmold with the same cross-sectional area, without needing more space in the earmold for larger vent diameters. The objective occlusion was measured via REM. The listeners vocalized the vowel /ee/, and REOR<sub>voc</sub> and REUR<sub>voc</sub> were measured. The results showed that the occlusion caused by the Flex-Vent™ was significantly lower than that using conventional earmolds and confirmed the relationship between the acoustic mass and the occlusion effect, that is, reduction of the acoustic mass for shorter vents.

Jespersen et al. (2006) evaluated the “Flex-Vent™” system with unilaterally and bilaterally fitted hearing aids. The vent system was compared with those of conventional earmolds with parallel vents of 1.6 and 2.4 mm diameter, CIC dummy hearing aids, and non-occluding silicone eartips. The listeners (normal-hearing and hearing-impaired) were required to evaluate the naturalness of their own voice in the unilateral and bilateral conditions while reading a text aloud. The results for all listeners showed less subjective occlusion for the FlexVent™ and for non-occluding eartips than for the conventional parallel vents, as expected from the acoustic mass of the systems. The hearing-impaired and the normal-hearing listeners perceived more occlusion when fitted bilaterally than unilaterally for all earmolds except the non-occluding eartips.

### Open-Fit Hearing Aids

#### Definition of Open-Fit Hearing Aids

Open-fit hearing aids are defined according to the patent of Fretz, Stypulkowski, and Woods (2001, p. 9 column 3) as follows: “An open ear canal hearing-aid system comprises an ear canal tube sized for positioning in an ear canal of a user so that the ear canal is at least partially open for directly receiving ambient sounds.” The hearing aid is placed in a case (behind the ear) and connected via a tube and a soft tip to the ear canal. The tubes and the soft tips can consist of different soft materials and have various lengths, shapes, and diameters. In other styles of open-fit hearing aids, the receiver is placed within the ear canal and is connected with wires to the BTE case. Those styles are identified as receiver-in-the-canal (RIC) or receiver-in-the-ear hearing aids. The name “open fit” is mostly restricted to BTE styles with or without the receiver in the canal, although ITEs with a large vent diameter or a short vent length, called the “Ipsilateral Routing of Signal” (IROS) vent, can physically be regarded as open fit.

The different hearing-aid manufacturers use various coupling systems between the hearing aid and the ear canal: individual earmolds or earshells made of acrylic

with different vent diameters, Receiver-In-The-Aid (RITA) hearing aids with thin tubes and different silicone domes, or RIC hearing aids where the receiver is embedded in an acrylic earmold or in a dome. The domes are available with different openness and are separated into open (small bores), closed (no bores), and so called double or power (depending on manufacturer specifications or publications), which seal even more tightly than the closed type. The proper dome or vent size is suggested by the fitting software, depending on the hearing loss and required gain setting.

### Vent Sizes

As described earlier, Kuk and Keenan (2006) observed a reduction in the objective occlusion effect by about 4 dB for each widening of the vent diameter by 1 mm. Depending on the length of the vent, this would require vent diameters of up to 5 mm to fully avoid the occlusion effect. Unfortunately, due to space limitations or disadvantages described further below, such a vent diameter may not be possible. In the end, Kuk and Keenan (2006) recommended choosing the vent size according to the hearing loss at 500 Hz: If the hearing loss is 20 dB HL or less, open-fit hearing aids should be used. If it is between 20 and 30 dB HL, vent diameters of 3 mm or above should be used, and, for every 10 dB increase in hearing loss, the vent diameter should be decreased by 0.5 mm. If no feedback cancellation algorithm can be activated in the hearing aid, a decrease in vent diameter of 1 mm is advised. Kiessling et al. (2003) recommended that open-fit hearing aids should not be used for a hearing loss larger than 70 dB HL above 2 kHz. This limitation is a consequence of the gain available at high frequencies before acoustic feedback occurs. For more severe hearing losses at high frequencies, narrow-vented or closed systems should be used. This limit in hearing loss corresponds well with the reported maximum gain for open fittings at high frequencies of 34 dB (Mueller, 2009). However, the threshold values for different vent sizes given by Kiessling et al. (2003) and Kuk and Keenan (2006) should be reconsidered when using state-of-the-art feedback cancellation systems (Holube, Puder, & Velde, 2014), but revised data are not yet available. Additionally, Kießling (2006) discussed the benefit and use of open-fit hearing aids for listeners with noise-induced hearing loss caused by noise exposure at work. He did not recommend using open fittings in these work locations, since noise can be delivered through the open vent and may compromise the ear.

### RIC and RITA Hearing Aids

Hoen and Fabry (2007) compared RIC hearing aids to traditional BTEs having custom-made earmolds and full-

shell ITEs for listeners with moderate-to-severe hearing losses. In contrast to ITEs, which are worn in the ear and have a microphone and receiver close to each other, RIC hearing aids enlarge this distance by including the microphone in the BTE housing and the receiver in the ear canal. This larger distance reduces the transmission of sound from the receiver to the microphone and, as shown in a simulation by Hoen and Fabry (2007) allow larger vents or higher gain before feedback occurs, as compared with a full-shell ITE. They also pointed out that the residual volume in the ear canal is smaller for a RIC hearing aid than for a traditional BTE or ITE device because RIC hearing aids can be placed closer to the eardrum. Hence, due to smaller residual volume more gain is available for more moderate to severe hearing losses for a given vent size, or a larger vent can be used for a given maximum gain.

Hallenbeck and Groth (2008) determined whether there are differences in maximum stable gain for the two open-fit options, RIC, and RITA hearing aids, using the same dome size. Differences, for example, due to fewer possibilities for sound to feedback into the microphone because of a larger distance between receiver and microphone in the RIC hearing aids, might influence the decision process for one or the other option or dome style. In that study, noise-reduction and feedback-cancellation algorithms were deactivated to observe only mechanical and acoustical influences. The acoustic leakage of the dome was the primary pathway for feedback, regardless of the receiver placement. Hence, the results showed no difference in maximum available gain between the two device types.

Differences between domes styles (open, occluded, and power) were examined by Coburn, Rosenthal, and Jensen (2014) for RIC hearing aids. They observed less acoustic leakage out of the ear canal for the power style, but below 1 kHz, the open and occluded domes performed similarly. Hence, occluded domes do not result in the same sealing of the ear canal as individually custom-made earmolds without a vent and do not allow for the same amount of gain before feedback occurs. In addition, Coburn et al. (2014) observed quite large individual differences and recommend using REM to assess fitting results.

A survey revealed different opinions about whether RIC hearing aids are advantageous over RITA hearing aids (Mueller, 2009). A round table of audiological experts described by Mueller (2009) also discussed the findings of the survey. Data supporting most of the statements were not published or even collected. For example, tubes might cut-off high frequencies (6 to 9 kHz) and RIC hearing aids are possibly a good choice for an extended high-frequency responses. In contrast to the survey results, the experts agreed that maximum gain before feedback is the same for RIC and RITA hearing

aids and, therefore, agreed with Hallenbeck and Groth (2008). The overall agreement was that, independently of the hearing aid, REM is very important to fit hearing aids appropriately.

### *Fitting of Open-Fit Hearing Aids*

A hearing aid is programmed to its first fit setting via the fitting software of the manufacturer, while taking the individual hearing loss into account. This hearing loss determines the required frequency- and level-dependent sound pressure level at the eardrum, which should be provided by any hearing aid, conventional or open-fit (Dillon, 2006). Nevertheless, the openness of the ear canal affects the achieved sound level, due to leakage of low frequencies out of the ear canal and due to reduced maximum stable gain at high frequencies before feedback occurs. For example, Kuk and Keenan (2006) showed a reduction in maximum stable gain from about 50 dB to about 20 dB around 2 to 3 kHz using a thin tube with domes as compared with closed fittings. According to Kuk and Keenan (2006), the available gain is increased by about 10 dB when using a feedback-reduction algorithm. The resulting maximum available gain of 30 dB approximates the 34 dB mentioned by Ricketts in the round table of audiological experts (Mueller, 2009) assuming an increase of available gain by 16 dB.

Regardless of the same required targets for open and closed fittings, the restriction in maximum stable gain might result in a modification of the fitting formula applied by the manufacturers. An example was given by Chalupper and Kanasmascheff (2008). They modified the initial target gain curves when, due to the openness of the ear canal, the required gain at high frequencies was not achievable. For the modifications, psychoacoustical models for speech recognition and loudness were used to calculate modified gains. The goal of the models was to maximize speech recognition while protecting the hearing-aid users from excess amplification. For severe high-frequency hearing losses, gain at those frequencies might not contribute to speech recognition. Therefore, Chalupper and Kanasmascheff (2008) claimed that the modifications often resulted in higher gain for medium frequencies which are more effectively usable. A comparison of the modified fitting rule to NAL-NL1 (Byrne, Dillon, Ching, Katsch, & Keidser, 2001) in a small group of hearing-aid users revealed similar speech recognition scores and, due to reduced gain at high frequencies, less occurrence of feedback.

On the other hand, modifications to the fitting formula of the manufacturer due to open fittings are often difficult, and fittings might be inaccurate. Aazh, Moore, and Prasher (2012a) showed that 71% of the open fittings examined deviated from the NAL-NL1 targets by

more than 10 dB. All but 18% could be modified based on REM to reduce the deviations to less than 10 dB. Therefore, maximum available gain was not the primary factor responsible for the mismatches. The nature of the modifications to the fitting software when selecting the coupling style (earmold, dome, or RIC) and the vent size are generally not revealed by the manufacturers. Therefore, the reasons for differing fitting results are difficult to explore.

One factor that has to be taken into account by the fitting formula is the amount of gain for low-frequency sound with open fittings. In any hearing-aid fitting, the vent size influences the effect of sound leaking into the ear canal as well as out of the ear. Especially low frequencies will escape through large vents (Dillon, 2012). Hence, it is difficult to achieve substantial gain at low frequencies with open fittings. The interaction between the amplified sound from the hearing aid partly leaking out of the ear canal and the direct sound via the vent into the ear canal needs to be taken into account for the fitting process in general. If the level difference between the amplified and direct sound exceeds 10 dB, the more intense sound dominates. Up to 1,500 Hz, the vent-transmitted (direct) sound in an open-fit hearing aid usually dominates the result. Thus, the hearing aid's signal processing has no influence up to this frequency (Dillon, 2012). The interaction of the direct and amplified sound and their impact for open fittings are described later in the Direct and Amplified Sound section.

With increasing vent diameter, more direct sound at the low frequencies degrades the performance of directional microphones and of noise-reduction algorithms. This disadvantage can be partly compensated by higher low-frequency gain settings to increase the amplified sound relative to the direct sound. Unfortunately, higher gain settings are often not possible due to the large amount of sound leaking out of the ear canal. Keidser, Carter, Chalupper, and Dillon (2007) measured how much low-frequency gain is preferred by listeners to compensate for leakage out of the ear canal through the vent. Hearing-impaired listeners were fitted with BTE or ITE hearing aids with clinically appropriated vent sizes. Keidser et al. (2007) evaluated hearing-aid settings that differed in the amount of real-ear insertion gain at 250 Hz for a 65 dB SPL broadband speech-weighted noise signal and in the activation or deactivation of adaptive features (directional microphone and noise reduction). The evaluation of the various settings was carried out using different methods. A diary was used to describe acoustical situations and to rate the performance of the settings during a 4-week field trial. In the laboratory, speech recognition tests, paired comparisons for speech in babble noise, and tests on horizontal localization were performed. On average, all listeners with a target insertion gain of 3 dB or less preferred no gain for

the amplified sound, that is, a dominance of the direct sound at 250 Hz over higher gain settings that resulted in a dominance of the amplified sound. Only listeners with more severe hearing losses at 500 Hz, which resulted in an insertion gain of more than 3 dB at lower frequencies, preferred higher gain settings that result in amplifier-dominated sound at low frequencies.

## Advantages of Open-Fit Hearing Aids

This section focuses on the advantages of open-fit hearing aids compared with BTEs with (nearly) closed earmolds or foam tips.

### Subjective Evaluations

In many studies, listeners were asked to evaluate their own voice and the quality of other sounds for open and closed fittings (e.g., Gnewikow & Moss, 2006; Jespersen et al., 2006; Kiessling et al., 2005; Laugesen et al., 2011; MacKenzie, 2006; Otto, 2005; Taylor, 2006). Participants had normal hearing or mild to severe hearing losses and very different experiences with hearing aids. Sometimes, the participants' own hearing aids were used, whereas in other cases, specific test hearing aids were fitted. Hearing-aid fittings were done mostly using NAL-NL1 first fit. If the participants experienced any discomfort, only slight modifications were applied. The subjective impression was rated using various questionnaires, for example, Satisfaction with Amplification in Daily Life (SADL, Cox & Alexander, 1999), Abbreviated Profile of Hearing Aid Benefit (APHAB, Cox & Alexander, 1995), Glasgow Hearing Aid Benefit (GHAB, Gatehouse, 1999), International Outcome Inventory for Hearing Aids (IOI-HA, Cox & Alexander, 2002), and self-created ones. The subjective ratings indicated more natural sound quality, an enhancement of own-voice perception, and higher satisfaction with open than with closed fittings.

### Localization

More direct sound, as well as sound resulting from head- and outer-ear diffractions, will reach the tympanic membrane for open-fit than for closed fittings, and this might improve localization performance. Byrne, Noble, and Glauerdt (1996) evaluated the horizontal and the vertical localization performance of normal hearing listeners and listeners with sensorineural, conductive and combined hearing losses, and various hearing aids and earmolds. The listeners were seated in a loudspeaker array and identified the active loudspeaker after each presentation. The group results did not confirm the expected localization improvement for open fittings relative to closed fittings. Nonetheless, the choice of earmold affected the localization performance of some participants.

Horizontal localization performance was also analyzed in the study of Keidser et al. (2007) described earlier. The listeners were fitted with BTE hearing aids and individual earmolds, or ITEs with different vent sizes (1.5 mm up to open). In general, there was no significant difference in localization performance for different low-frequency gain settings, that is, even 0 dB of gain at low frequencies seemed to provide enough information for localization. In addition, front-back discrimination was improved by directional microphones, even for the setting with a gain of 0 dB at low frequencies. These results imply that open fittings are not in conflict with localization requirements.

### Everyday Life

Taylor (2006) evaluated the benefit of open-fit hearing aids compared with closed fittings for experienced and for first time hearing-aid users. The hearing aids were fitted to meet the NAL-R targets (Byrne & Dillon, 1986). The experienced hearing-aid users answered questions from the MarkeTrak and Amplifon Satisfaction Surveys. For the MarkeTrak survey, all listeners were more satisfied with the new hearing aids than with the old ones. Within the experienced hearing-aid users, overall satisfaction was nearly the same for the open and closed groups. The open-fit hearing aids were rated better with respect to sound quality of the user's own voice, appearance, localization, wind noise, and sound of chewing or swallowing. For categories such as feedback using the telephone, wax accumulation or understanding on the telephone, the ratings were similar. The new hearing-aid users filled out the IOI-HA and APHAB questionnaires. The IOI-HA responses showed a benefit for using hearing aids as compared with the unaided situation. The ratings for the IOI-HA were markedly better for the open-fit hearing aids for hearing-aid usage, residual activity limitation, and residual participation restriction. The results of the APHAB showed no significant difference between the open and closed groups. Taylor (2006) concluded that for the hearing loss of the participants in the study, open-fit hearing aids have a few features (own-voice perception, localization, and appearance) that make them more favorable than closed hearing aids for some patients.

## Disadvantages of Open-Fit Hearing Aids

### REM

REMs provide the audiologist with information about the sound pressure level in the ear canal and are recommended for fitting hearing aids. For this purpose, the sound level in a specific room with a loudspeaker in front of the listener or at 45° to the side can be calibrated

according to ANSI S3.46 (1997) and ISO 12124 (2001) using three different methods:

- Substitution method:
  - Calibration with a reference microphone at the position of the listener's head but with the listener absent.
  - Normally not used in audiology
- Modified pressure method with stored equalization:
  - The listener is present and at the right position.
  - The sound pressure level is measured near the listener's ear, using the reference microphone. The result is used as a reference for the following measurements within the ear canal using the probe microphone while the reference microphone is switched off.
  - The listener has to be in the same position during the entire measurement.
- Modified pressure method with concurrent equalization:
  - The listener is present and at the right position.
  - The sound pressure level is measured near the listener's ear using the reference microphone. The calibration is done continually during the measurement by adjusting the sound pressure level at the reference microphone to the desired value.
  - Movements of the listener during the measurements are automatically compensated.

Unfortunately, amplified sound in the modified pressure method with concurrent equalization can leak back to the reference microphone and influence the calibration, or rather the adjustment of the loudspeaker amplification, in open fittings. Therefore, the modified pressure method with stored equalization is recommended for open-fit hearing aids. Alternatively, the reference microphone should be positioned at the opposite ear with the loudspeaker at 0° azimuth (e.g., Dillon, 2012; Lantz, Jensen, Haastrup, & Olsen, 2007; Mueller & Ricketts, 2006). The accuracy of the modified pressure method with stored equalization was evaluated by Shaw (2010), and the results indicated that the method is clinically applicable. On the other hand, differences between the two modified pressure methods, with stored equalization and with concurrent equalization, are only observed for hearing aid gain settings of more than 20 dB and, therefore, do not seem to be necessary for mild to moderate hearing losses (Aazh, Moore, & Prasher, 2012b; Mueller & Ricketts, 2006).

### Interaction Between Direct and Amplified Sound

Direct and amplified sound superimpose in the ear canal. At those frequencies where they have the same amplitude

and are in phase (due to time delays of multiples of one period), the sound level is increased by 6 dB. At those frequencies where they have the same amplitude and a phase difference of 180° (due to time delays of odd-numbered multiples of half a period), they cancel and generate a notch in the frequency response. For other phase relationships and different levels of direct and amplified sound, the amplitude after superposition is somewhere in between. Alterations in the frequency response based on this superposition are visible if direct and amplified sound differ in level by less than 10 dB (Dillon, 2012; Mueller & Ricketts, 2006) and are called "comb-filtering." Although this general physical principle exists for any hearing-aid style, it is more likely to happen, and in a higher frequency range, in open than in closed-fit hearing aids and, compared with conventional hearing aids, may result in perceptual changes (Bramsløw, 2010; Dillon, 2012; Kuk & Keenan, 2006).

Bramsløw (2010) evaluated the impact of time delays between direct and amplified sound on sound quality using different high-pass cut-off frequencies available in the hearing aid to avoid comb-filtering at lower frequencies. The results for hearing impaired and normal-hearing listeners showed no clear preference with regard to delays of 5 to 10 ms, although artifacts were audible. The listeners preferred the high-pass filter with 2,200 Hz cut-off frequency compared with the lower (100 Hz and 1,250 Hz) cut-off frequencies in terms of sound quality, irrespective of the time delay applied. In contrast to Bramsløw (2010), Stone, Moore, Meisenbacher, and Derleth (2008) showed that the impact of comb-filtering effects on disturbance ratings seems to be small for different simulated conditions, but that the delay between the amplified and direct sound should be less than 5 ms.

A possibility for reducing comb-filtering effects of open-fit hearing aids is the so-called Direct Sound Compensation (DSC). This algorithm automatically ensures that amplification is not applied for frequencies that are already directly audible through the vent. A dynamic process avoids the comb-filter effect by comparing the estimated frequency- and input-level-dependent REOG and REAG. When the REAG does not exceed the REOG by a given amount, the amplification of the hearing aid is switched off, so that an adverse overlap of direct and amplified sound is avoided. The difference between REOG and REAG is calculated in a frequency-dependent way, and the effect of the DSC is increased for high-level input as more direct sound relative to amplified sound reaches the eardrum as compared with low-input levels (Phonak, 2010). So far, data on sound quality with DSC are not publically available. Latzel, Boretzki, and Chalupper (2012) described the influence of DSC on REM and recommended leaving DSC, if available, activated during REM to determine the real insertion gain at the tympanic membrane.

## Signal Processing Algorithms

Fortune (1997) evaluated the effect of different vent sizes on compression ratios in the ear canal measured via REM. The used sizes ranged from unvented up to IROS (diameter of 4.75 mm). He presented stimuli at different input levels using wide dynamic range compression with a low compression threshold and different settings of the compression ratios. When plotting the output level in the ear canal versus the presented input level, the inverse of the slope gives the “actual” compression ratio. The “actual” compression ratios were lower for the IROS vent than for the other vent sizes, the difference increasing with increasing compression ratio. Fortune (1997) explained this as follows: With increasing input level, the gain is reduced for wide dynamic range compression, resulting in a higher level of the direct sound relative to the amplified sound in the IROS condition and in the reduction of the gain decrease and compression ratio.

Additional hearing-aid features such as directional microphones, noise reduction, and any adaptive algorithms of a hearing aid are implemented to improve speech recognition or reduce listening effort in noisy situations. If the direct sound, which is not affected by the hearing aid’s signal processing, dominates the amplified sound, the benefit of directional microphones, and of noise reduction is decreased. This is especially the case at lower frequencies and at higher input levels, where hearing aids provide no or low amplification. Directionality can be altered even if the amplified sound is 10 dB higher in level than the direct sound and is reduced or vanishes at lower ratios between amplified and direct sound (Dillon, 2012). In the case of small vents or closed earmolds, the amplified sound dominates the direct sound over a large range of frequencies and levels, and the benefit from directional microphones is increased.

Bentler, Wu, and Jeon (2006) confirmed these assumptions by evaluating the effectiveness of directional microphones for open-fit hearing aids on an artificial head (Knowles Electronic Manikin for Acoustic Research, KEMAR). For directivity, the results showed frequency- and level-specific limitations in open-fit hearing aids. Bentler et al. (2006) observed that the effect of the directional microphone was maximal at low and moderate input levels.

Ricketts (2000) quantified the directivity of different hearing aids and evaluated the effects of several parameters such as venting, microphone port orientation, and compression using KEMAR. The earmolds were full shell earmolds with 0- to 2-mm vents and a loose fitting called “open.” The open vent, in combination with a directional microphone, showed significantly higher directivity than the omnidirectional mode. Nevertheless, the directivity at 500 Hz decreased with increasing vent size and at 1 kHz, the Directivity Index was significantly higher for the closed vent than for the open vents.

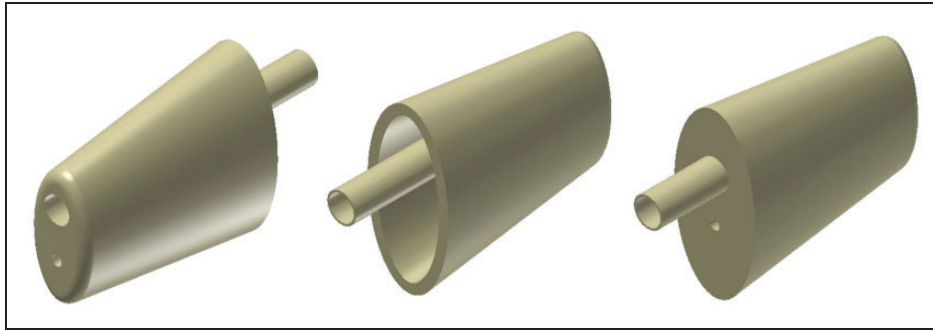
These technical measures are consistent with the results of speech recognition tests. Magnusson, Claesson, Persson, and Tengstrand (2013) measured the speech recognition threshold (SRT) for two earmolds, one acryl shell without vent, the other with thin tube and open dome, using the Hagerman sentences (Hagerman, 1982). The SRT for 50% correct speech did not differ between unaided listening and the aided configuration in the omnidirectional mode, regardless of whether open or closed fittings were used. Using the directional microphones, the open and closed configurations showed significant improvements in SRT (open: 1.6 dB and closed: 4.4 dB) compared with unaided listening. For directional microphones combined with noise reduction, the SRT was improved by 3.3 dB using a closed-fit compared with an open-fit hearing aid, showing the advantage of directional and noise reduction features in closed relative to open fittings. Nevertheless, the improvement in speech recognition due to directional microphones with open fittings relative to unaided or omnidirectional microphones was significant. This result was confirmed by other studies showing improvements between 1.6 and 3 dB, depending on the specific measurement configurations applied in the studies (Fabry, 2006; Flynn, 2004; Klemp & Dhar, 2008; Kuk et al., 2005b; Magnusson et al., 2013; Valente & Mispagel, 2008), especially when attempts were made to maximize the directional effect at high frequencies.

Another signal processing algorithm implemented in hearing aids is feedback cancellation. This was a prerequisite to the success of open-fit hearing aids in the last decade. Blau, Sankowsky, Stirnemann, Oberdanner, and Schmitt (2008) showed that the maximum stable gain before feedback occurs is reduced in open-fit hearing aids with domes by 25 dB and in hearing aids with closed domes by 15 dB, relative to that obtained with individual earmolds. Feedback reduction algorithms allow for gain increases of 10 to 16 dB (Kuk & Keenan, 2006; Mueller, 2009) and, therefore, a much broader fitting range of up to 70 dB HL at high frequencies. Unfortunately, feedback reduction algorithms can produce artifacts and, therefore, compromise sound quality, especially for music. Hence, gain reductions or more closed fittings should be considered if music-loving patients complain about artifacts.

## Alternative Approaches

### *Mechanical Modification*

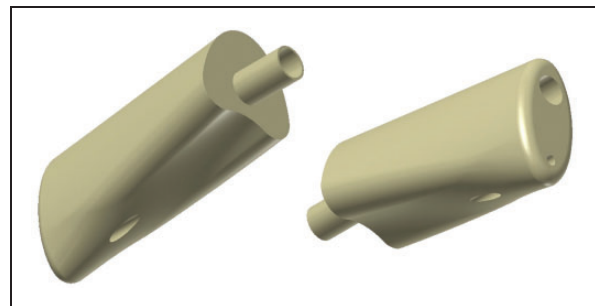
One possibility for reducing occlusion is to position the earmold in the bony part of the ear canal (Dillon, 2012; Gudmundsen, 1994; Killion, 2003; Zwislocki, 1953). Less occlusion-generated sound is obtained compared with earmolds within the cartilaginous part of the ear canal. Lee and Casali (2011) compared earplugs inserted either



**Figure 3.** Sketch of a “hollow” (middle) and a “solid” (right) earmold described by Kuk et al. (2009).

shallowly or deeply into the ear canal using REM. They found less objective occlusion effect for the deep versus the shallow sealing. For deeply seated earmolds, the ear impression needed to be taken very carefully. Alternatively, a deeply seated dome could be used (Staab, 2003). Caldarola (2013) described another option for a deeply inserted earshell. The case is smaller than for a conventional CIC and is not in contact with the ear canal walls, which allows for venting via gaps, thus decreasing occlusion. The case is held in place with a flexible mounting member at its tip. Practical experience with this invention is not yet available. Difficulties inserting and removing the earmolds by the users might occur, as well as discomfort while wearing deeply seated earmolds for long periods (Dillon, 2012).

Another class of inventions or ideas aims to lower the acoustic mass of the vent by maximizing its diameter or reducing its length. One advantage in comparison to standard open or closed domes might be the individual match to the outer ear or ear canal for improved mechanical fitting accuracy and wearing comfort. The following section describes a few of these. Bayer (2008) invented different mountings via a clip that is placed over an edge of the pinna to stabilize the sound tube in the open ear canal without using a dome. Kuk et al. (2009) proposed another mechanical modification for reducing the acoustic mass and, therefore, the occlusion effect. They determined objective occlusion via REM using a “hollow” and a solid earmold with different vent sizes (see Figure 3). The hollow earmold has only a thin shell and is hollow inside. The results for the hollow earmold were similar to those using open-fit hearing aids. Saile (2010) described a “nugget-earmold” (see Figure 4), which has a recess. The recess prevents contact of the earmold with the mandibular condyle (part of the lower jaw which moves the ear canal wall during articulation) and improves its movement flexibility. At the same time, the shortened vent reduces the acoustic mass. For stabilization, an additional anchor is needed in the concha, which can be achieved by conventional earmold styles (e.g., skeleton, semi-skeleton).



**Figure 4.** Sketch of a “nugget” earmold described by Saile (2010).

### Active Occlusion Reduction

Another possibility for decreasing occlusion while closing the ear canal, providing more gain, and possibly maximizing the effects of directional microphones and noise reduction algorithms is active occlusion reduction, an algorithm focusing on the low-frequency region. This algorithm requires an additional microphone to be located near the receiver at the output of the hearing aid (Bernier & Voix, 2013, 2015; Mejia, Dillon, & Fisher, 2008). The functionality of the algorithm for active occlusion reduction is similar to that of feedback reduction, that is, the occlusion sound is picked up in the ear canal, inverted in phase and added to the receiver signal. The phase shift of  $180^\circ$  between the original occlusion sound and the sound added to the receiver signal leads to cancellations and a lower sound pressure level. Mejia et al. (2008) implemented the active occlusion cancellation system into a hearing aid. Objective measurements with a completely sealed ear shell showed a decrease in the objective occlusion effect by 15 dB at 300 Hz. As a side effect of the phase shift, the level is increased for frequencies near 1.3 kHz by superposition of the original and the processed signal. Bernier and Voix (2013, 2015) found similar reductions in the low-frequency region where the occlusion effect is most prominent. In a second experiment of Mejia et al. (2008),

subjective measurements with normal-hearing listeners were conducted. The listeners were fitted bilaterally with ITE-prototypes without vent and had to rate the perception of their own voice while blindly switching between activation and deactivation of the occlusion cancellation algorithm. The occlusion cancellation algorithm led to less perceived occlusion and more comfort. Disadvantages of this system are that more space is required for the additional microphone, moisture, and wax can accumulate at the microphone port, and additional signal processing is required (Dillon, 2012).

### Variable Vent

Within the last decade, several inventions have been proposed to adjust the vent size while wearing the hearing aid. Those inventions are based on the assumption that when the user is talking, low gain, and a large vent are required. Other listening conditions, especially in quiet environments, require higher gain settings with an increased risk for feedback and would, therefore, benefit from smaller vents. Different vent sizes can be achieved electronically as suggested by Lehnertz (2002), Fischer (2010), and Feucht, Naumann, and Rass (2013). The idea is to have an actuator that detects the user's own voice or different acoustical situations and opens or closes the vent via, for example, an electroactive polymer. The electroactive polymer is placed in the vent or on the sides of a dome and is controlled by the hearing aid. The classifier of the hearing aid should differentiate between the user's own voice, quiet environments, feedback, or music. If own voice or loud situations are detected, the polymer will open the vent, while it will close it for quiet environments or if feedback is identified. To improve the fit in the ear canal, the housing of the earmold's cone can be manufactured with an inflatable volume around it (e.g., Blendinger, 2014; Gebert, 2012; Naumann, 2012). Studies are needed to evaluate the practical value of these inventions.

### Summary and Conclusions

While wearing a hearing aid, the ear canal is sealed to a variable extent by an earmold or earshell. A major complaint of hearing-aid users in this situation is occlusion. Occlusion can be separated into its objective and subjective effects. Objective occlusion is defined as the difference in sound pressure level between the occluded and the open ear canal during self-vocalization of a vowel and is mainly present at low frequencies. Subjective occlusion is defined in terms of the change in perception of the user's own voice through sealing the ear canal, which is evaluated via questionnaires or paired comparisons. An important factor governing objective and subjective occlusion is the acoustic mass of the vent. Open-fit hearing aids can help reduce

objective and subjective occlusion as well as improve sound quality, localization, and wearing comfort. But there are also some limitations for open-fit hearing aids. First, in REM the verification of hearing-aid fittings should be carried out via the stored equalization method if the required REIG is larger than 20 dB. Second, the interaction of the direct and amplified sounds can cause audible artifacts and can lower subjective sound quality. Third, the benefit of adaptive features such as directional microphones or noise reduction algorithms can be decreased, and the available maximum gain before feedback is reduced. Within the fitting process of hearing aids, the hearing loss is still the main factor governing the choice of the vent, the prescribed gain and the feature settings, but the audiologist should consider the individual needs and circumstances of the listeners. Hearing aids with hollow earmolds, domes, or a large vent are suitable for listeners with near-normal low-frequency hearing and mild to moderate hearing loss of up to 70 dB HL at mid and high frequencies. Otherwise, more closed fittings are recommended. To increase the benefit of adaptive features and still offer less occlusion to listeners with more severe hearing losses, active occlusion algorithms should be considered.

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