WIDEXPRESS NO.25

JULY 2010

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AISA: AN ACCURATE METHOD FOR ASSESSING THE **ACOUSTIC EFFECT** OF THE **EARMOULD**

INTRODUCTION

One of the cornerstones of hearing aid fitting is acoustic accuracy. Without control of the sound at the eardrum, there is a risk that hearing aid users are insufficiently or overly compensated for their hearing loss, and well-substantiated and optimised hearing aid signal processing features may lose power. Ultimately, deficient management of the acoustics may therefore negatively impact the hearing aid user's performance and satisfaction.

A major challenge in fitting hearing aids is to ensure that the actual gain applied at the individual eardrum matches the gain prescribed by the fitting rationale. This is not a trivial matter, since the sound pressure at the eardrum depends on the anatomy of the individual ear and, particularly, on the degree of openness of the acoustic fitting.

When wearing a hearing aid, the sound pressure level at the hearing aid user's eardrum is not only determined by the output of the hearing aid, but is also influenced by the effect of any ventilation (vent) present in the hearing aid's shell or mould, or leakage between the earmould and the walls of the ear canal. The vent affects the sound pressure at the eardrum in two ways. Firstly, the sound from the hearing aid loses intensity at lower frequencies, resulting in a "tinny" quality. This effect, termed the vent effect, is defined as the difference in hearing aid generated sound pressure level, measured at the eardrum, after the introduction of a vent into the shell/ear mould. Secondly, sound also finds its way to the eardrum directly through the vent. This is referred to as the directly transmitted sound. The sound heard by the hearing aid user is the sum of these sound sources at the eardrum.

AISA provides a way to accurately assess the overall acoustic effect of the earmould in-situ. The technique can for instance be employed to estimate the acoustic changes introduced by the vent from a single measurement. This estimate can then be used to compensate for the effect of the vent to ensure that the prescribed gain is in fact provided at the eardrum.

It is a general misconception that the physical vent diameter alone produces the vent effect. While it is true that the vent diameter is the most influential parameter (Lybarger, 1985), it is possible to identify at least five major variables which influence the magnitude of the vent effect: Vent diameter, vent length, leakage, residual volume, and middle ear properties. Thus, simply knowing the vent length and vent diameter does not automatically allow one to accurately predict the effect of a vent. If you rely exclusively on the gain of a hearing aid and the vent dimensions of the earmould to predict the output, the in-situ output may be very different from the intended output. Each of the five major variables will be discussed later on.

ASSESSMENT OF IN-SITU ACOUSTICS

A COMPLEX MODEL

Central in AISA is a complex model of the in-situ response of a hearing aid which relates the maximum gain before feedback to the vent effect and direct sound. We have based the development of our acoustic computer simulation tools on the available knowledge about the acoustic behaviour of receivers, tubing, ear canal, etc. (e.g., Blackstock, 2000; Brüel & Kjær, Product data sheet; Egolf, 1980; Egolf et al., 1988; Flanagan, 1972; Hudde & Engel, 1998; Keefe, 1984; Lampton, 1978; LoPresti, 2000; Stinson, 1989; Stinson & Lawton, 1989). In such a simulation, it is possible to simulate changes, such as a larger ear, a leakage, or vent size, and see what they may do to the sound pressure in the real world. In the same way, it is possible to compare measurements from the real world to simulated measurements and change parameters in the simulation to make the simulated measurements look like the real world measurements.

The model, which is a transmission line model, comprises a block schematic model with each component in the acoustic path, including the hearing aid receiver, tubing, ear and eardrum, vent, leakage radiation and hearing aid microphone. The model makes it possible to predict the relative sound pressure with a high degree of accuracy for all types of hearing aids. This way, the feedback test, the vent effect and the directly transmitted sound can be simulated for any given vent size.

In the next sections, the transmission line model is used to analyse the acoustic consequences of certain key variables in the properties of the earmould and the user's ear.

ESTIMATION OF THE VENT EFFECT

In the following, the vent effect is analysed in depth. As stated above, at least five major variables - vent diameter, vent length, leakage, residual volume, and middle ear properties - influence the vent effect. Thus, simply knowing the vent length and vent diameter does not automatically permit an accurate estimation of the vent effect. An accurate prediction of the vent effect requires an assessment with the earmould in place. AISA makes it possible to estimate the in-situ acoustics in the ear, including the vent effect, from a single measurement. How and why this is possible will be discussed in more detail in the following.

THE VENT EFFECT AND THE HELMHOLTZ RESONANCE

The vent effect is defined as the change in the sound from the hearing aid receiver, measured at the eardrum, with the introduction of a ventilation channel through the earmould.

The vented in-situ hearing aid is, in essence, a Helmholtz resonator, which functions in the same manner as a bottleneck when somebody blows over the opening. The bottleneck is the vent and the bottle itself corresponds to the residual volume between the earmould and the eardrum.

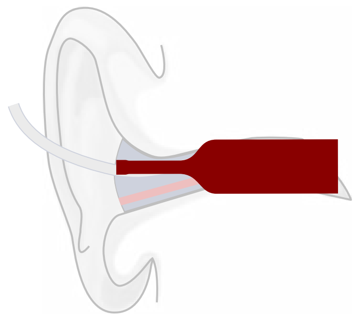

Figure 1. The vent and the residual ear canal function like a bottle.

The Helmholtz resonator may be excited by three sources of sound: sound from the hearing aid receiver, external sound, and vibrating ear canal walls during own speech. For all three sources, the system will resonate at the Helmholtz frequency, which is the main resonance frequency in the ear canal once an earmould has been inserted. Since the vented hearing aid is essentially a Helmholtz resonator, the vent effect always has a similar shape as a function of frequency, characterised by a resonance frequency (i.e., the frequency at which sound is amplified), a frequency-dependent attenuation below that frequency, and no effect above the frequency.

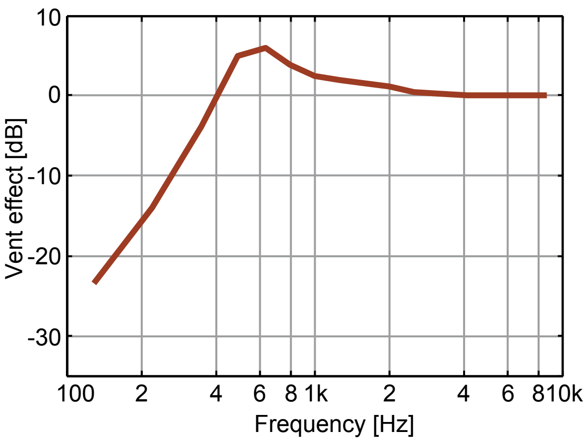

Figure 2. Vent effect in a hearing aid. Its shape is always the same with a resonance frequency at which sound is amplified, a frequency-dependent attenuation below the resonance frequency, and no effect above the resonance frequency.

The resonance frequency is dependent on the length and diameter of the vent, and the volume of the residual ear canal, but the curve is always shaped as described above. Therefore, in essence, in a system where all parameters are clearly defined, the vent effect may be denoted by a single parameter, for instance the vent diameter, which mirrors the frequency of the Helmholtz resonance. This fact is what makes it possible to apply AISA to hearing aids. AISA detects the Helmholtz resonance frequency and predicts how the resonator will influence the different sound sources at the eardrum.

FACTORS INFLUENCING THE IN-SITU OUTPUT

In the following sections, factors which influence the Helmholtz resonance frequency will be described by means of the vent effect. The section is based on simulations reported in Kuk and Nordahn (2006). It is recommended to read the article for further details.

PHYSICAL DIMENSIONS OF THE VENT

As mentioned above, the most influential parameter to affect the vent effect is the physical dimensions of the vent. We can see in figure 3 below that as the vent diameter increases, the output in the low frequencies decreases, and the resonance frequency moves to a higher region.

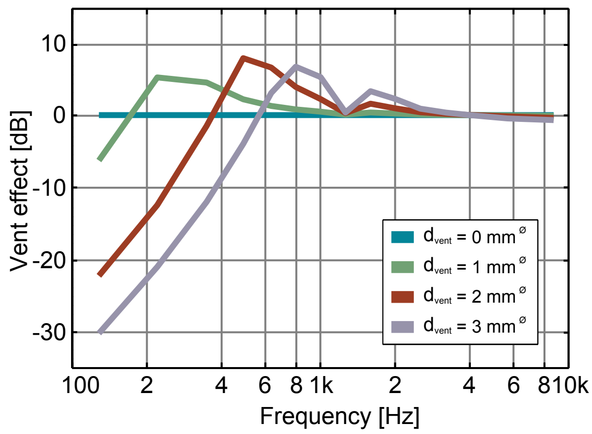

Figure 3. Effect of vent diameter on the output of a hearing aid. A 3 mm vent reduces the output at 200 Hz by as much as 23 dB compared to a closed earmould (ø= 0 mm). Reproduced from Kuk & Nordahn, 2006.

Figure 4 below shows the effect of the length of the vent on the vent effect. We can see that as the length increases, the amount of low frequency attenuation decreases, and the resonance frequency shifts to a lower region.

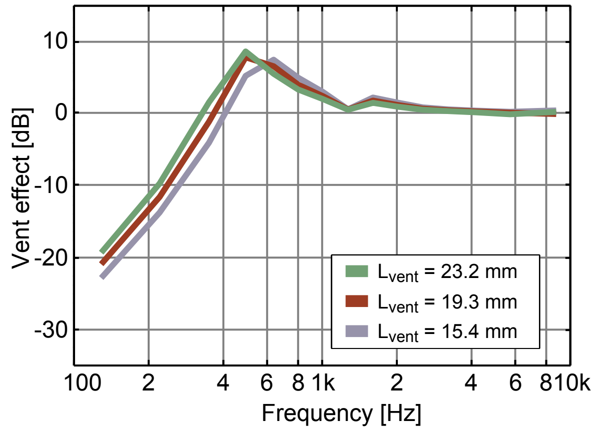

Figure 4. Vent effect as function of frequency for different vent lengths. An increase in length results in a decrease in low-frequency gain reduction and a shift of resonance frequency to a lower region. A vent diameter of 2 mm is used in the example. Reproduced from Kuk & Nordahn, 2006.

In summary, as the vent diameter increases, low-frequency attenuation increases, and the resonance frequency shifts to a higher frequency region. In contrast, as vent length increases, attenuation in the low frequency decreases, and the resonance frequency occurs in a lower region. Put in a different way, what we can see in the two figures above is that a decrease in the length of the vent will produce the same effect as an increase in the vent diameter; viz., a larger vent effect.

LEAKAGE

Leakage, defined as the unintentional venting which may occur between the earmould and the ear canal wall, can also influence the vent effect. Geometrically, a leak can be considered as a slit with a certain height, width and length.

Figure 5 below shows the output as different leaks are introduced into an earmould with a 2 mm^Ø vent. The leaks are assumed to exist over the entire length of the earmould, and a quarter of the way around the mould. The height of the leaks is 0.05 mm (small), 0.2 mm (medium), and 0.5 mm (large), corresponding to cylindrical vent sizes of 0.9 mm^Ø, 1.6 mm^Ø and 2.5 mm^Ø, respectively. We can see that as the size of the leak increases, attenuation in the low frequencies also increases, and the resonance frequency shifts to a higher region.

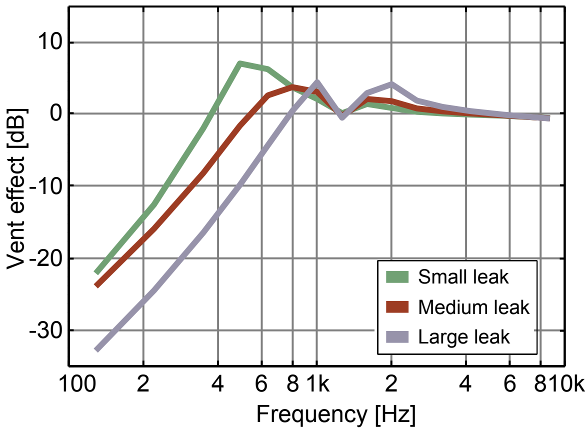

Figure 5. Effect of different degrees of leakage on the vent effect. The example is based on an earmould with a 2 mm vent diameter. Reproduced from Kuk & Nordahn, 2006

In other words, we can see that a large leak will produce the same result as a large vent diameter; viz., a large vent effect.

RESIDUAL VOLUME IN THE EAR CANAL

The residual volume between the earmould and the eardrum can influence the vent effect too.

Figure 6 below shows the vent effect in three different residual ear canals: A small (0.5 cc), regular (0.7 cc), and large (0.9 cc) ear canal volume between the mould and the eardrum. We can see that the largest vent effect is found with the small ear, i.e. the small ear has a higher amount of low-frequency attenuation, and the resonance frequency occurs in a higher region than is the case with the regular and large ears. The resonance will also have a smaller effect than in a regular and large ear.

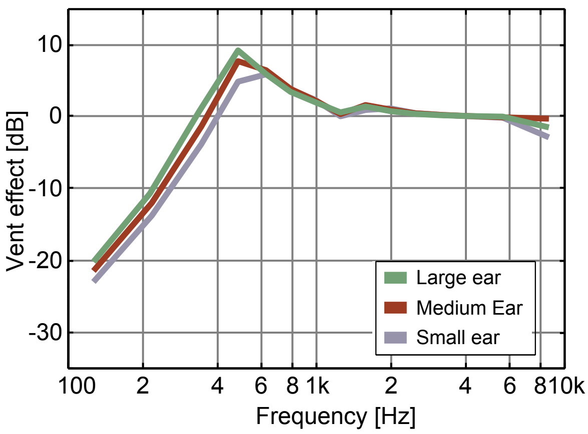

Figure 6. Effect of residual ear canal volume on the vent effect. The largest vent effect is seen with the small ear. The example is based on a vent with a 2 mm diameter and a length of 19.3 mm. Reproduced from Kuk & Nordahn, 2006.

If we compare figure 6 above with figure 1, which shows the effect of vent diameter, we can see that a small ear will produce a similar effect as a large vent diameter; viz., a large vent effect.

MIDDLE EAR PROPERTIES

In addition to the length and diameter of the vent and the volume of the residual space between the mould and the eardrum, the Helmholtz resonance also depends on the compliance (freedom of movement) of the eardrum.

Figure 7 below compares the vent effect of an ear with otosclerosis and an ear with ossicular discontinuity to that of a normal ear. The ear with the otosclerosis has a less mobile eardrum compared to a normal ear. The ear with ossicular discontinuity, on the other hand, has a hyper-mobile eardrum compared to a normal ear.

Inspection of figure 7 reveals that, in comparison with a normal ear, a hyper-mobile eardrum will have less low-frequency attenuation, and the resonance frequency will occur in a lower region. A stiff eardrum, on the other hand, will have more low-frequency attenuation, and the resonance will occur in a higher frequency region. The resonance will also have a greater effect than in a normal ear.

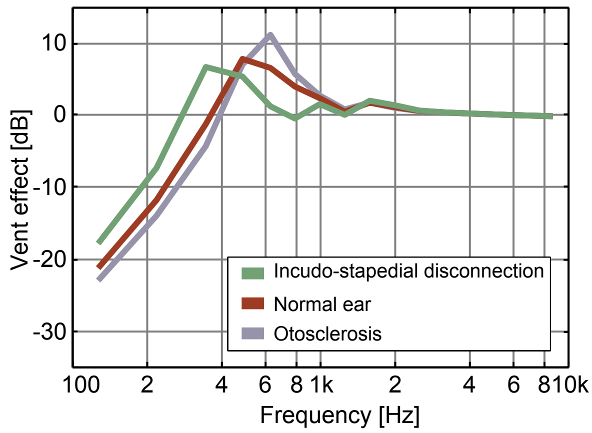

Figure 7. Simulated effect of middle ear compliance on the vent effect. The example is based on an earmould with a 2 mm vent diameter and a length of 19.3 mm. Reproduced from Kuk & Nordahn, 2006.

If we compare the effect of middle ear compliance as shown in figure 7 above to the effect of vent diameter as shown in figure 1, we can see that a stiff eardrum has the same effect as a large vent diameter; namely that it increases the vent effect.

THE CENTRAL ROLE OF THE FEEDBACK TEST

The feedback test measurement, which is performed during the fitting of a Widex hearing aid, is conducted in the clinic with the hearing aid placed in the user's ear. The first step in AISA involves an estimation of the equivalent vent size (explained below) by means of the feedback test.

The feedback test is performed routinely during the fitting procedure by playing a signal with the hearing aid receiver and picking up the acoustic signal with the one or more microphones. The result of the feedback test relates systematically to the size of the vent, and is therefore suitable for estimating an equivalent vent size. More specifically, vent diameter affects high frequency output by limiting the maximum gain before feedback.

Figure 8 below illustrates the relationship between vent diameter and maximum gain before feedback. We can see that, with a closed earmould (the blue curve), as much as 70 dB of gain is available in the low frequencies, while only 50 dB is available in the high frequencies. As the vent diameter increases, the available gain decreases.

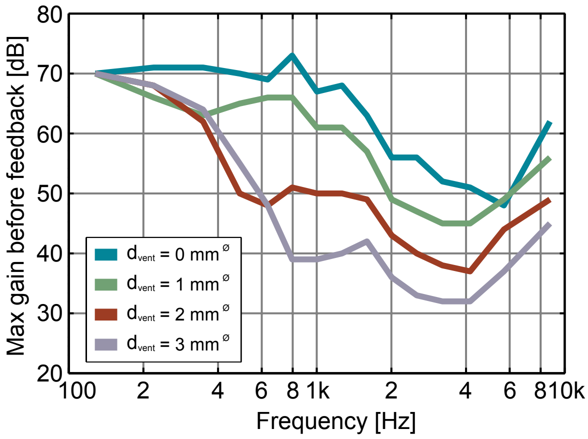

Figure 8. Maximum gain before feedback as a function of different vent diameters. As the vent diameter increases, the available gain decreases. The decrease is more rapid in the high frequencies than in the low frequencies. Reproduced from Kuk & Nordahn, 2006.

The result of the feedback test is compared to an average simulated hearing aid user stored in the fitting software. By changing the vent size in the simulation until the simulated measurement is similar to the real world measurement, it is possible to make a very accurate prediction regarding the vent effect in the real fitting. The vent size needed in the simulation to match the real world feedback test result is then shown as the in-situ vent size in Compass.
Three sets of simulated data have been included in the fitting software for each vent diameter: Results from simulated feedback tests with different vent sizes, vent effect, and directly transmitted sound (i.e., sound passing into the ear canal through vent and leaks without amplification from the hearing aid). Thus, when the hearing care professional performs the feedback test, the measured data is compared to the simulated data, and the vent diameter which gives the best fit between the measured and simulated feedback test is identified. This is denoted the equivalent vent diameter.
Having obtained the equivalent diameter, we also have an accurate model of the vent-related acoustics in the individual hearing aid user's ear. This makes it possible to estimate a number of acoustic parameters, including the vent effect, directly transmitted sound, etc. With this information at our disposal, we have the tools to estimate the total sound pressure at the eardrum in ventilated fittings.

LEAKAGE IS INCLUDED IN THE ESTIMATION OF THE VENT EFFECT

Widex uses the feedback test to take a snapshot of the acoustics, so to speak. This snapshot includes any leakage between the earmould and ear canal wall. In fact, it is almost impossible to achieve a completely sealed ear mould without hurting the user while inserting the mould into the ear. A certain degree of leakage will always be present, and the acoustic effect will depend on the quality of the ear impression and the mould itself. For particularly poor moulds, the uncontrollable leakage between the earmould and ear canal wall will even differ from insertion to insertion during daily life. AISA takes the in-situ leakage into account when estimating the equivalent vent diameter during the fitting session. This has at least two advantages:

- The vent estimate, and therefore also the fitting, becomes more precise
- A large difference between the physical and estimated vent size indicates to the hearing care professional that the earmould is poor

In Compass, the estimated vent size is shown after the feedback test is performed (In-situ vent effect).
In a fitting session where the physical vent size in a CIC is, for instance, 1 mm^{ø} and AISA says that it is 2.5 mm^{ø}, the hearing aid may squeal. This may lead to the erroneous conclusion that AISA is making the hearing aid squeal. The truth is that the somewhat larger estimate of the vent size is a sign that there is a huge leakage between the earmould and ear canal wall which makes the hearing aid squeal.

CORRECTION FOR THE VENT EFFECT

Once we have obtained an accurate idea about how the sound pressure at the eardrum is altered as a result of the vent effect, we are able to correct for it. The purpose of correcting for the vent effect is to obtain a greater degree of control with the sound pressure at the eardrum, so that the in-situ gain will be as close to the intended target as possible.
The assessment of the in-situ acoustics and the subsequent gain correction involve four main stages:

1) In-situ assessment of the acoustic effects of the vent.
2) Correction of the Sensogram on the basis of the estimated vent effect.
3) Calculation of gain on the basis of the corrected Sensogram.
4) Correction of insertion gain.

Correction for vent effect is relevant for all signals generated by the receiver in the hearing aid, i.e. Sensogram and insertion gain. The effect of the vent on the feedback test was already established when estimating the equivalent vent diameter. The correction of the Sensogram and the insertion gain will be discussed below.

CORRECTION OF THE SENSOGRAM

When the Sensogram is measured with a ventilated earmould, some of the low frequency sound will be attenuated below the hearing threshold. The hearing care professional must therefore increase the level of the Sensogram tones accordingly to identify the hearing thresholds. In the example in figure 9 below, a Sensogram threshold of about 60 dB has been measured at 250 Hz with a 2.5 mmø vent in a person with a flat 50 dB hearing loss. However, using this result would mean that gain would not be calculated according to the actual hearing loss, but on the basis of the hearing loss in combination with the vent effect. This would result in an inaccurate fitting. Therefore, the Sensogram must be corrected for the vent effect before the required insertion gain for the individual hearing loss is calculated. This is automatically done by the fitting software.

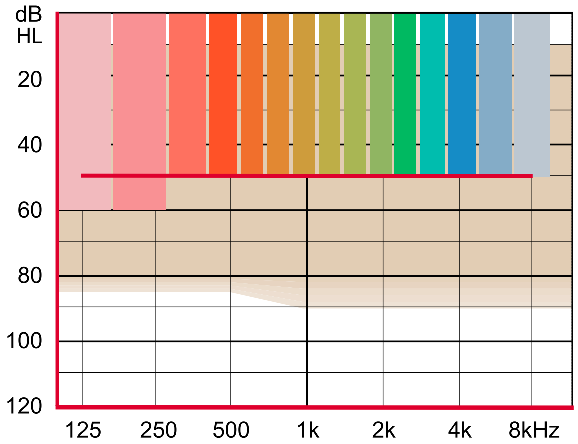

Figure 9. Example of a Sensogram measured with a 2.5 mm vent. According to the audiogram, the person has a 50 dB flat hearing loss. The Sensogram threshold is 60 dB for 125 and 250 Hz, however.

CORRECTION OF THE INSERTION GAIN

When the receiver produces sound, the sound pressure at the eardrum will be reduced as a result of the vent effect. Therefore, the insertion gain must also be corrected for the vent effect in order to ensure the audibility of low frequency sounds. For simplicity's sake, let us continue with the example from the previous section and assume that a hearing aid user has a true hearing loss of 50 dB and a measured Sensogram threshold of 60dB at 250 Hz due to the vent effect of 10 dB. Using the half-gain rule (Lybarger, 1944, 1963) as an illustrative fitting rationale, a hearing loss of 50 dB leads to a target gain of 25 dB. However, if we apply an insertion gain of 25 dB, the actual amplification will only be 15 dB due to the 10 dB vent effect. So the vent effect must be taken into consideration when the appropriate insertion gain is calculated. In the example, an insertion gain of 35 dB would be needed to obtain the target gain of 25 dB.

WHAT ABOUT THE FUTURE?

Efforts are constantly made to ensure that AISA provides the most accurate picture of the in-situ acoustics in every situation. The possibilities offered by AISA in terms of ensuring precise gain prescription will be explored to the widest possible extent in future products for even further precision in fitting.
The following implementations in connection with AISA will be available in WIDEX CLEAR440 and future products:

- Sound Harmony is introduced for flex fittings. In other words, the possibility of compensating for directly transmitted sound by making bands transparent (explained in the section below) in ventilated (i.e., flex) fittings will be available.
- A small adjustment of the limit for when bands are made transparent in open fittings.
- Optimisation of average earmould data for even more precision in flex fittings.

The purpose of these implementations is to optimise fitting accuracy even further for the benefit of the individual user's comfort.
The main benefits of the changes in AISA in relation to ventilated fittings are summarised below:

- Band transparency will minimise the risk of uncertainty with respect the amount of gain which is applied caused by phase disruption.
- The hearing care professional may choose a very open ventilated earmould and obtain roughly the same REIG as with an open fitting.
- Internal noise is eliminated in the transparent bands. This gives a quieter and more stable impression of the sound.

SOUND HARMONY IN FLEX FITTINGS

As a novelty, Sound Harmony is available for flex fittings in WIDEX CLEAR440 and future product releases. Originally introduced in connection with open fittings, Sound Harmony comprises two major steps. The first central step involves a compensation for the reduction in sound pressure in the low frequencies. The second step involves turning off the amplification in those bands where the compensation leads to the directly transmitted sound and the amplified sound being about equal in level (the term 'band transparency' refers to the turning off of bands) to avoid uncertainties with respect to how much gain is given.
With a completely closed earmould, there is no vent

through which external sound can leak in. However, with a flex fitting there will always be a certain amount of directly transmitted sound leaking in through the vent or leaks. In Figure 10 below, the REIG (real ear insertion gain) for an external sound source is indicated by the red curve. The curve includes both the contribution from the hearing aid sound and the direct sound. The green curve shows the insertion gain (IG), which is the sound from the hearing aid in isolation. The blue curve shows the isolated direct sound when the hearing aid is turned off.

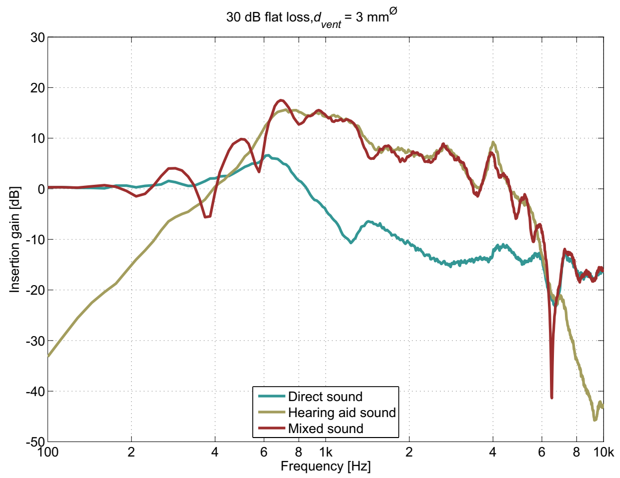

Figure 10. An example of the mixing of the insertion gain and the directly transmitted sound at the eardrum.

It may be observed that the green curve slopes radically below the Helmholtz resonance around 650 Hz. This is due to the vent effect and reflects that the low frequencies are attenuated. It can also be seen that the directly transmitted sound dominates over the hearing aid sound at low frequencies. This is partly a result of the vent effect having attenuated the hearing aid sound, and partly a result of the direct sound leaking in through the vent unattenuated at low frequencies. This gives rise to two phenomena:

- The stronger of the directly transmitted sound and the in-situ insertion gain dominates the total gain.
- An acoustic phenomenon called phase disruption, which occurs when the directly transmitted sound and the insertion gain are equally strong, while the relative phase varies. Phase disruption leads to uncertainties with respect to the amount of eardrum gain which is actually applied. These uncertainties are seen as ripples on the REIG (red curve).

Sound Harmony makes sure that gain application is always under control by making bands transparent when the direct sound and the hearing aid sound are at the same level. The necessary information for making the relevant bands transparent in a particular frequency range is made available through AISA:

1. We know the expected REIG at the eardrum for a closed fitting. This is part of any hearing aid's default data, based on coupler measurements done by the hearing aid manufacturer.
2. We know how the vent changes the hearing aid sound at the eardrum (the estimated vent effect).
3. We know how external sounds are attenuated by the vent (the estimated direct sound).
4. We thus know the strength ratio between the hearing aid gain and the direct gain.

The above information enables us to evaluate the strength ratio and set up a rule about when bands should be made transparent.

Slight change in fitting rationale based on the in-situ vent effect estimate for further precision

When performing a flex fitting, there is always a risk that the fitting may in effect be more acoustically open than intended because of leakage and earmould fit. AISA is the feature that ensures compensation in gain based on an in-situ estimate of the acoustics of the fit. In WIDEX CLEAR440 and future hearing aid products, the compensation applied in accordance with the fitting rationale on the basis of the in-situ vent effect estimate will be changed slightly for even more precision in all fittings.
In flex fittings, the possibility of making bands transparent is introduced to ensure that flex fittings which are in effect acoustically open will have compensation of gain. Band transparency in flex fittings will depend on whether a critical limit is reached.
A number of bands can also be made transparent in open fittings if the critical limit is reached. Moreover, a minor adjustment in the critical limit will result in slightly fewer bands being made transparent.

AVERAGE EARMOULD DATA

Our fitting rationale was developed with unsealed earmoulds, with the risk of unintended leakage between the earmould and ear canal wall. In product ranges up to and including mind, the model of the in-situ hearing aid included no leakage, but emulated a completely sealed earmould. In future products, however, the more realistic situation, where a small leakage is unavoidable for hard earmoulds, will constitute the reference earmould. This is relevant for the shape of the modelled vent effect data, which becomes a bit less pronounced (slightly shallower slope at low frequencies). The effect will be relatively small, but it has been implemented all the same since it produces a more realistic gain estimation for closed earmoulds that are not completely sealed.

SUMMARY AND CONCLUSION

Accurate gain prescription requires knowledge of how the hearing aid will perform in the user's ear. AISA (Assessment of In-situ Acoustics) is a technique by which the in-situ acoustics in the ear can be estimated from a single measurement. This can be used to accurately assess the acoustic changes introduced by the vent in the earmould and compensate for the vent effect in the prescribed gain.

The vented in-situ hearing aid is, in essence, a Helmholtz resonator. AISA detects the Helmholtz resonance frequency on the basis of a measurement obtained by means of the user's hearing aid and transforms this measurement into an estimate of the vent effect.

Once an accurate estimate of how the sound pressure at the eardrum is altered as a result of the vent, AISA is also able to correct for it. Corrections are relevant in connection with the Sensogram, the insertion gain and the directly transmitted sound (Sound Harmony). The purpose of correcting for the vent effect is to obtain a greater degree of control with the sound pressure at the eardrum to ensure that the in-situ gain will be as close to the intended target as possible.

We are constantly striving to ensure that AISA provides the most accurate picture of the in-situ acoustics possible. The possibilities offered by AISA in relation to precise gain prescription will be explored to the widest possible extent in future products.

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