Contralateral masking for monaural speech intelligibility measurements with hearing aids in free-field speech conditions

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Patients with asymmetrical hearing loss or unilateral hearing loss often suffer from bad hearing at the poor side, from localisation problems, and from poor speech understanding in noise. In many cases speech audiometry in free field can be an effective tool to decide whether speech understanding is equivalent for both aided ears, making binaural interaction possible, but only if the speech intelligibility is measured for each ear separately. However, it is difficult to evaluate the effectiveness of each (aided) ear individually. This is due to the fact that sound generated in free field can reach both ears, i.e., also the non-test ear. The sound can reach the non-test ear in three ways: directly from the loudspeaker, indirectly by transcranial transmission via the test ear (cross-hearing), or via the skull. In many clinics the non-test ear is "masked" by a foam plug and/or earmuffs. This method helps to minimise the effect of hearing direct sound at the non-test ear. However, transcranial transmission cannot be ruled out by this method. We suggest a new method of contralateral masking, while stimulating in free field. Theoretical considerations are outlined to determine the masking levels necessary to mask sufficiently, and to avoid too much masking (over-masking). For most asymmetric hearing losses a simple rule can be used.

INTRODUCTION

We often use speech audiometry in free field condition to measure the effect of amplification of a hearing aid on speech intelligibility. Speech is presented by a loudspeaker, received and amplified by the hearing aid, and presented to the ear. This way we investigate speech intelligibility with hearing aids.

In many cases it is useful to measure the contribution of each hearing aid separately. When wearing two hearing aids we like to know whether both hearing aid settings produce equal speech intelligibility. By measuring the effect separately for each hearing aid and for both hearing aids together, it is possible to compare the hearing aid settings and measure the binaural advantage. Asymmetry between hearing loss in

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both ears is common. Also in that case it is good to know whether comparable intelligibility can be realised for both ears.

However, measuring aided speech intelligibility for each ear is not simple, because the non-test ear can also contribute to the result. There are three ways in which the speech from the loudspeaker can reach the non-test ear:

1. Speech from the loudspeaker reaches the non-test ear directly by air.
2. Speech from the loudspeaker is amplified by the hearing aid in the test ear and is transcranially transmitted to the cochlea of the non-test ear.
3. Speech from the loudspeaker is conducted by the skull to the non-test ear.

The main question is how to make sure that speech coming from the loudspeaker is not heard by the non-test ear.

In the following parts we will discuss what happens when the test ear is not plugged or masked. After that we will discuss how to avoid hearing in the non-test ear. Then we will discuss problems with masking, i.e., over-masking. Finally, the clinical relevance and rules will be discussed.

MEASURING MONAURALLY WITHOUT PLUGGING THE NON-TEST EAR

As mentioned in the introduction, speech from the loudspeaker reaches also the non-test ear. Whether speech is intelligible also in the non-test ear depends on the size of the hearing loss in the non-test ear.

Using the speech audiogram (Fig. 1) we can observe when speech is intelligible in the non-test ear at normal speech levels. From the example of Fig. 1 we observe from the middle panel that speech at a level of 65 dB SPL is partly intelligible for the left ear. It must be kept in mind that the speech audiogram in Fig. 1 applies to monaurally presented speech by TDH-39 headphones. For speech presented by a loudspeaker in a free-field condition the normal curve will approximately be 3 dB better (ANSI S3.6). However for a level of 3 dB above the speech threshold the speech score is still very low. Therefore, we do not consider this shift. So, from Fig. 1 we observe that measurement of speech intelligibility with a hearing aid on the left is possible at 65 dB SPL because there is no speech intelligibility in the right ear at this speech level. On the other hand, the effect of a hearing aid on the right side on speech intelligibility in free field cannot be reliable measured, because the free-field speech is also intelligible in the left ear. Blocking or masking of the left ear is needed for measurement of the effect of the hearing aid on the right side.

ATTENUATION USING AN EAR PLUG (OR EAR MUFF)

If the non-test ear is plugged with an earplug that attenuates with an amount of D dB, then the speech level in the non-test ear is S–D dB. The widely used foam plugs have an attenuation of at least 10 dB in the lower speech frequencies and even more for higher frequencies. This is the assumed protection value, APV, which is calculated (per frequency) as the mean attenuation minus the standard deviation (3M

Occupational Health Group, 2009; 2010; Berger, 1984). When covering the ear by an extra earmuff, the APV increases to 25-30 dB (Berger, 1984). In the example of Fig. 1, it means that the use of an earplug in the left ear is not sufficient to make free-field speech unintelligible for a speech level of 75 dB SPL in all individuals. But the combination of an ear plug and an ear muff would be a suitable solution.

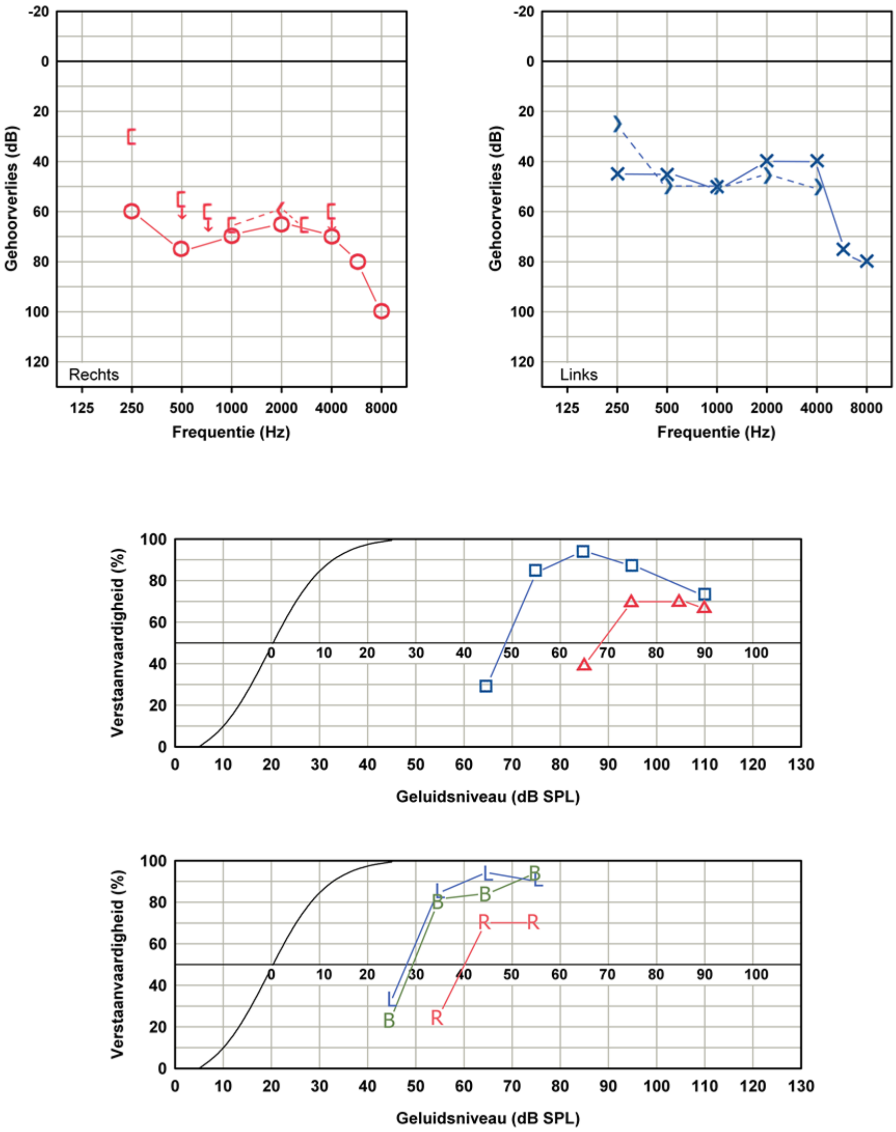

Fig. 1: Upper panel: tone audiogram. Middle panel: Speech audiogram including normal psychometric curve. The monaurally measured phoneme score (% correct) of Dutch CVC words is plotted as a function of speech level in dB SPL. Bottom panel: Free-field speech intelligibility measurements with hearing aids. Masking of the contralateral ear with an insert phone at a level of N = S – 10 was applied for the ‘R’ curve.

In cases with a large conductive hearing loss in the non-test ear the use of ear plug and/or muff is not sufficient, because the skull conducts free-field sound to the cochlea. The minimum attenuation of this signal path is 45 dB, according to Zwislocki (1957) and Berger *et al.* (2003). Thus, the speech may be above the nearly normal bone conduction thresholds in the non-test ear.

THE USE OF MASKING NOISE

From the foregoing it appears that speech in the range of 50-80 dB SPL might be intelligible in the non-test ear, despite using a plug or muff. Therefore masking is required in the non-test ear in such cases.

For presentation of masking noise, insert phones like Etymotics ER-3A and 5A are very suitable. These insert phones have foam plugs that have relatively high attenuation. This means that less masking noise is needed. According to the data sheet of insert phone ER-3A an attenuation of at least 20 dB is possible in practically all ears at any frequency in the range 125-4000 Hz. But the effective attenuation depends on insertion depth (Clark and Rosser, 1988). For more shallow insertion the attenuation is less than 20 dB. To minimize the risk of insufficient damping an attenuation value of 10 dB will be used and a careful insertion is highly recommended.

The speech level in the non-test ear is S–D when using insert phones.

Therefore, speech will just be masked in the non-test ear when the noise level N is:

$$N = S - D \text{ or } N = S - 10 \qquad \text{(Eq. 1)}$$

Notice that we assume that the speech noise used for masking is calibrated such that, for a speech-to-noise ratio of 0 dB on the audiometer dials, speech is not intelligible.

For ear problems with increased ear volume (radical cavity, tympanic membrane tube, and tympanic membrane perforation) the actual noise level of the insert phone may be less (Voss *et al.*, 2000). For these cases, we choose N = S.

AVOIDING HEARING IN THE NON-TEST EAR BY CROSS-HEARING

As already mentioned in the introduction, there is a second way how speech from the loudspeaker can reach the non-test ear. Speech is amplified by the hearing aid in the test ear and is transcranially transmitted to the cochlea of the non-test ear. The question now is: Is the masking noise level N = S – D in the non-test ear large enough to prevent hearing the transcranially transmitted sound?

Speech with level S is amplified by the hearing aid with a certain gain. The amplified speech is attenuated with an intra-aural attenuation of the amplified sound (IA_{HA}, Interaural Attenuation hearing aid) before it reaches the non-test ear. IA_{HA} depends on the tightness of the fit of the earmould and is also frequency-dependent. For tightly fitted ear moulds and deeply placed in-the-canal hearing aids IA_{HA} can be as low as 45 dB, but typically the interaural attenuation is at least 60 dB (Fagelson *et al.*, 2003; Valente *et al.*, 1995; Gudmundsen, 1997; Munro and Contractor, 2010).

The speech level in the non-test ear due to transcranial transmission is:

$$S + Gain - IA_{HA} \quad \text{(Eq. 2)}$$

Speech at this level is only intelligible, at least in part, if it is above the bone conduction levels of the non-test ear.

From this formula, it is clear that the risk that speech might be intelligible in the non-test ear is greatest if the gain of the hearing aid is large and the bone conduction thresholds in the non-test ear are low.

The amount of noise that is needed for proper masking of this transcranially transmitted speech is:

$$N = S + Gain - IA_{HA} + ABG\_non\text{-}test\ ear \quad \text{(Eq.3)}$$

where ABG_non-test ear is the air-bone gap in the non-test ear. A volume correction might be applied for increased ear volumes (0 or 10 dB).

Now we have two masking rules: Eq. 1 for calculation of the masking level that prevents speech intelligibility in the non-test ear when speech reaches the non-test ear directly, and Eq. 3 that is used to calculate the masking level necessary to prevent speech intelligibility in the non-test ear that reaches the ear transcranially.

The highest masking level from the two calculations has to be used.

Equation 3 prescribes more masking noise than Eq. 1 if:

$$Gain + ABG\_non\text{-}test\ ear > IA_{HA} - D \quad \text{(Eq. 4)}$$

With IA_{HA} = 60 dB and D = 10 dB:

$$Gain + ABG\_non\text{-}test\ ear > 50 \quad \text{(Eq. 5)}$$

Thus, in most cases the masking level from Eq. 1 is sufficient. Only in special cases like the application of a power hearing aid or a large air-bone gap in the non-test ear, the noise level needs to be calculated from Eq. 3.

IS OVER-MASKING POSSIBLE?

It is important to verify that masking noise in the non-test ear can be overheard in the test ear. This will mask the speech in the test ear. The risk of over-masking is most prominent when an air-bone gap is present in the test ear. This is due to the relatively favourable bone conduction thresholds in the test ear.

In order to have a near 100% speech score the masking noise in RMS value should be 10 dB lower (Fig. 2). Thus, to avoid over-masking there should be a signal-to-noise ratio (SNR) of 10 dB at the cochlea of the test ear. This corresponds to an SNR on the audiometer dial settings of 30 dB, due to calibration of the noise as a fully masking noise at dial settings that are equal for speech and noise. These values were derived from the psychometric curve of speech in noise with Dutch CVC words (Fig. 2). Other speech materials possibly need other values.

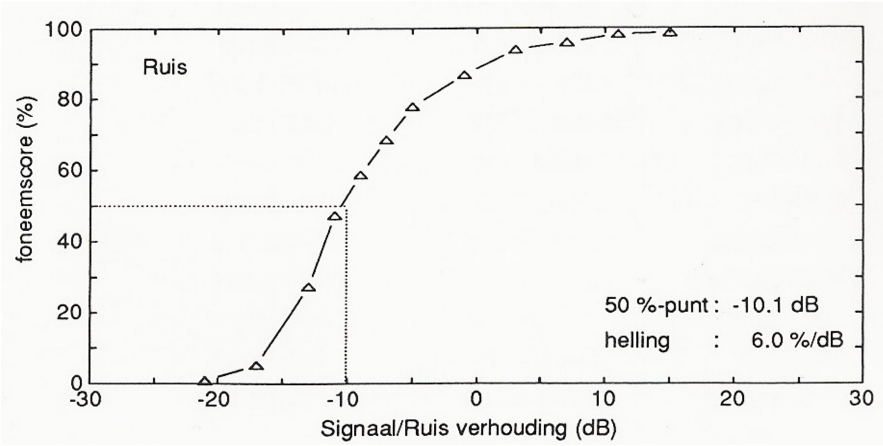

Fig. 2: Normal curve for Dutch CVC words in speech-shaped noise. The phoneme score (% correct) is plotted as a function of the signal to noise ratio (SNR in dB). For an SNR of −10 dB a percentage of 50% of the words are reported correctly.

For ears with a sensorineural hearing loss the SNR must be even better than for normal hearing. We assume that there will be over-masking when:

$$S - N \leq 40 \qquad \text{(Eq. 6)}$$

In the test ear the effective speech level is:

$$S + Gain - ABG\_test\ ear \qquad \text{(Eq. 7)}$$

The effective noise level is equal to the noise level in the non-test ear minus the interaural attenuation of the insert phone (IA_{IP}). This inter-aural attenuation is at least 55 dB (Munro and Contractor, 2010; Munro and Agnew, 1999; Sklare and Denenberg, 1987).

If Eq. 1 is used to determine masking noise level N, then there is a risk of over-masking when:

$$(S + Gain - ABG\_test\ ear) - (S - 10 + volume\ correction - IA_{IP}) \leq 40 \qquad \text{(Eq. 8)}$$

Hence, there is a risk of masking when:

$$ABG\_test\ ear - Gain + volume\ correction \geq 25 \qquad \text{(Eq. 9)}$$

A hearing aid will compensate (largely) for the air-bone gap in the test ear, so with hearing aids, over-masking is very unlikely.

If Eq. 3 is used to determine the masking noise level N, then there is a risk on over-masking when:

$$(S + Gain - ABG\_test\ ear) - (S + Gain - IA_{HA} + ABG\_non\text{-}test\ ear + volume\ correction - IA_{IP}) \leq 40 \qquad \text{(Eq. 10)}$$

Test ear	Non-test ear	Masking
Sensorineural	Normal	N = S – 10 Under-masking and over-masking not possible
Sensorineural	Sensorineural	N = S – 10 Under-masking and over-masking not possible
Sensorineural	Conductive or Mixed	N = S – 10 + volume correction (0 or 10 dB) Risk of under-masking when: Gain + ABG_non-test ear ≥ 50 dB. Then use: N = S + Gain – 60 + ABG_non-test ear + volume correction (0 or 10 dB). Over-masking is very unlikely
Conductive or Mixed	Normal or Sensorineural	N = S – 10 Risk of under-masking when: Gain ≥ 50 dB. Then use: N = S + Gain – 60 + volume correction (0 or 10 dB). Over-masking is very unlikely
Conductive or Mixed	Conductive or Mixed	N = S – 10 + volume correction (0 or 10 dB) Risk of under-masking when: Gain + ABG_non-test ear ≥ 50 dB. Then use: N = S + Gain – 60 + ABG_non-test ear + volume correction (0 or 10 dB). Risk of over-masking with this second rule when: ABG_test ear + ABG_non-test ear + volume correction ≥ 75 dB Transcranial hearing cannot be avoided in cases with a large air-bone gap in both ears!

Table 1: Masking rules for all possible combinations of hearing losses for the case that a hearing aid is on the test ear and an insert phone is in the non-test ear for masking. Also rules are given that indicate when there is a risk of under-masking and over-masking. The alternative rules are given that apply in these cases.

Hence:

$$\text{ABG\_test ear} + \text{ABG\_non-test ear} + \text{volume correction} \geq 75 \qquad \text{(Eq. 11)}$$

This shows that if there is an air-bone gap for only one ear, over-masking is very unlikely. Only when a large air-bone gap is present for both ears, over-masking is possible.

CLINICAL IMPLICATIONS

For clinical practice it is important to use a simple rule that is applicable for most cases. Therefore, the measuring procedure is simplified: always use masking with insert phones, even though this is not strictly necessary in all cases.

The basic masking rule is:

$$N = S - 10 + \text{volume correction (0 or 10 dB)} \qquad \text{(Eq. 12)}$$

For the attenuation of the insert foam tip a conservative value of 10 dB is chosen, to guarantee that the rule is valid for different fitting in various ears.

In the case of conductive or mixed hearing losses, in certain cases there is a risk of under-masking or over-masking. This should be taken into account when interpreting the measurements. Table 1 gives masking rules for all combinations of hearing losses. In this table also rules are given when there is risk of under-masking or over-masking. When so, alternative rules can be found. Again, these rules are based on conservative estimations of interaural attenuation values from the literature in order to make the rules safe for various ears and patients.

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