Masking theory in pure tone audiometry
– Systematic lectures – Part 1

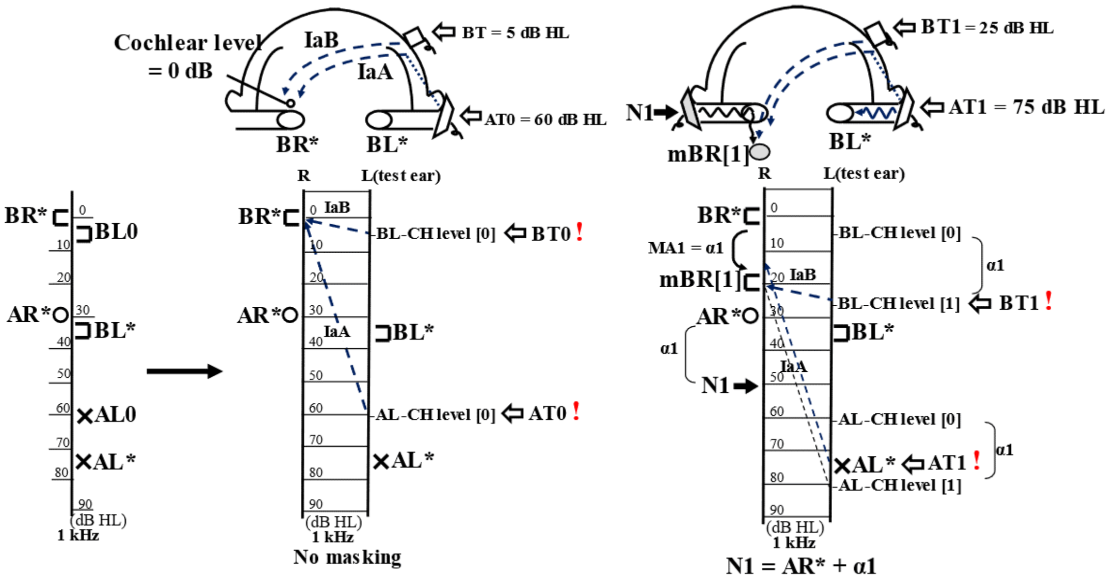
Part 1 Lecture 0: Introduction
Lecture 1: Transmission pathways and signal attenuation
Lecture 2: Definitions of terms

Lecture 1, 2: Focal point

To illustrate the concepts of cross hearing (CH), shadow hearing, and masking visually, a masking diagram is used. The vertical (frequency) axis on the audiogram at a given frequency is divided into the right and left axes. IaA and IaB are indicated by dashed lines between the axes.

AT0 is an air conduction (AC) test signal without masking. When AT0 of 60 dB HL is introduced to the left ear, it reaches the right inner ear at 0 dB HL (the cochlear level in the right ear = 0 dB HL), and is barely heard by that ear. With the initial masking noise (N1) of 50 dB HL in the right ear, the bone conduction (BC) threshold masked by N1 in the right ear (mBR[1]) is 20 dB HL. When AT1 of 75 dB HL, it is barely heard by the true BC threshold in the left ear (BL*).

IaA: Interaural attenuation for AC signals. IaB: Interaural attenuation for BC signals.
AR*: True AC threshold level in the right ear. AL*: True AC threshold level in the left ear.
BR*: True BC threshold level in the right ear. BT: BC test signal.
AL0: Apparent AC threshold in the left ear. BL0: Apparent BC threshold in the left ear
AL-CH level [0]: CH level for AC of the left ear without masking.
BL-CH level [0]: CH level for BC of the left ear without masking.



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Version 2: Sept. 2024
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Lecture 0: Introduction

0-1 Preface

The masking methods used in pure tone audiometry (PTA) are based on the basic principles of Hood's plateau method (Hood, 1960). In theory, there are no methods that operate beyond these principles. In audiometric configurations where typical plateaus are obtained, the plateau widths of the test ear are presented as follows:

APW = (IaA − the non-test ear's AB gap) + (IaA − the test ear's AB gap),

BPW = (IaA − the non-test ear's AB gap) + IaB,

where APW is an AC plateau width,

BPW is a BC plateau width,

IaA is the interaural attenuation for AC signals,

IaB is the interaural attenuation for BC signals, and

AB gap is an air-bone gap.

From these formulae, it can be said that if the AB gaps of both ears are equal to IaA, and IaB is 0 dB, then the APW and BPW are both 0 dB as well. This means that plateaus cannot be identified, and true thresholds cannot be determined, showing the theoretical limitations of masking.

The most important point of the formulae herein is that an AB gap can never be larger than IaA:

AB gap ≤ IaA.

This relationship is important because it is always present during all phases of masking, and should be kept in mind when thinking through masking problems. Therefore, the relationship is crucial to understanding the theoretical structure of masking and performing clinical masking efficiently.

The relationship AB gap ≤ IaA was clearly described by Luscher and Köning (1955) and Köning (1963) more than half a century ago. Later, Isogai (1986), Urabe et al. (1986, 1995), and Turner (2004) revealed its theoretical and clinical significance. However, the full implications of this relationship have not yet been elucidated, primarily due to two reasons. The first is that the simplest insights regarding the fundamental aspects of masking have not been fully shared. The second is the lack of tools for resolving masking-related problems such as X-Y coordinates and the calculus required for physical mathematics. As a result, the discussion scope about masking tends to diverge widely, and theoretical investigations have not yet been developed.

With these points in mind, this lecture series redefines the technical terms more strictly and presents new theoretical tools that can be used to describe the phenomena of clinical masking more precisely. In addition, we describe the fundamental structure of masking in a systematic way and attempt to clarify the theoretical and clinical limitations of the masking process. These lectures are intended for persons who desire a deeper understanding of masking. The intension is to help readers come to realize the full meaning of the relationship AB gap ≤ IaA, and thus grasp the whole picture of masking.

The following is an overview of this lecture series. Lectures 1 and 2 examine the basic issues and phenomena of masking, define the frequently used terms, and build a foundation for a common perception of masking. Adding to that foundation, the basic principles of the plateau method are discussed in Lecture 3. In Lectures 4 and 5, implications of the AB gap ≤ IaA relationship are explored. Then, based on these implications, the most rational masking method is described for use when there are differences between the AC thresholds in both ears. In Lecture 6, methods for solving the most problematic audiometric configurations are sought using Hood's principles and Rainville's method. In Lecture 7, the plateau widths are formulated, and the difficulty levels of masking are discussed. Finally, in Lecture 8, clinical masking procedures are addressed in view of clinical conditions, including measurement errors.

All of these lectures are based on studies originally published in the Japanese-language Journal Otologia Fukuoka in 1995 and 1996 and contain a broad range of new insights. The original articles are listed in the Reference section (Urabe et al., 1995, 1996).

0-2 A precondition for the theory: the ideal condition with no error

In Lectures 1 to 7, the ideal condition with no error is assumed as a precondition. However, in actuality, there is always a margin of error in our measurements. This means that, in principle, we cannot obtain “true values.” In other words, we can only obtain measurement values with either high or low accuracy levels, which include a certain amount of error. Therefore, before we can apply a theoretical method in a clinical setting, it is necessary to consider various clinical factors, including measurement errors (cf. Lecture 8). For example, when obtaining the AC threshold in the left ear, we refer to the sum of the errors derived from various clinical factors as the measurement error for the AC threshold in the left ear (ΔAL), and measured thresholds are discussed below.

(1) The true threshold in PTA

In PTA, hearing thresholds are measured in 5-dB steps. If a physical true AC hearing threshold level (HTL) in the left ear at some frequency is higher than 5 dB HTL and lower than or equal to 10 dB HTL, the left ear’s true AC threshold in PTA ($AL^{(*)}$) is 10 dB HTL (**Fig. 0-1**).

$$AL^{(*)} = 10 \text{ dB HTL}.$$

(2) The true threshold in measurement, including measurement errors

However, when **we** measure these thresholds, the measured values will inevitably have a certain amount of error. Hence, the left ear’s true AC threshold in measurement, including measurement errors, (AL^*) is given by

$$AL^* = AL^{(*)} + \Delta AL,$$

where ΔAL is the measurement error for the AC threshold in the left ear. **Fig. 0-2** shows a case in which the left ear’s true AC threshold in PTA ($AL^{(*)}$) is 70 dB HTL, and the right ear is completely deaf. If the AC threshold measured in the left ear without masking (AL0) is recorded as 75 dB HTL, then AL0 is the true threshold, not the shadow-hearing threshold, as will be described later (cf. **1.1-2 [1]**). To be exact, AL0 is equal to the left ear’s true AC threshold in measurement, including a measurement error of +5 dB (ΔAL0 = +5 dB):

$$AL0 = AL^* = AL^{(*)} + \Delta AL = 70 \text{ (dB HTL)} + 5 \text{ (dB)} = 75 \text{ dB HTL}.$$

If the measurement error is 0 dB (ΔAL0 = 0 dB), AL0 and AL* correspond to the left ear’s true AC threshold in PTA:

$$AL0 = AL^* = AL^{(*)} + \Delta AL = 70 \text{ (dB HTL)} + 0 \text{ (dB)} = 70 \text{ dB HTL} = AL^{(*)}.$$

The same is true for BC. Hence, the left ear’s true BC threshold in measurement, including measurement error, (BL^*) is as follows:

$$BL^* = BL^{(*)} + \Delta BL,$$

where $BL^{(*)}$ is the left ear’s true BC threshold in PTA and ΔBL is the threshold measurement error for the BC threshold in the left ear.

To further simplify the discussion, the ideal no-error condition is presumed to hold (ΔAL0 = 0 dB, ΔBL0 = 0 dB). More specifically, the true thresholds in measurement are always assumed to be equal to the true threshold in PTA ($AL^* = AL^{(*)}$, $BL^* = BL^{(*)}$).

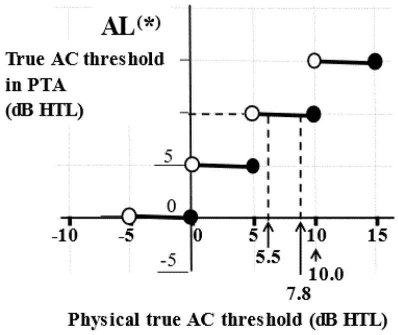

Figure 0-1 True AC thresholds in PTA

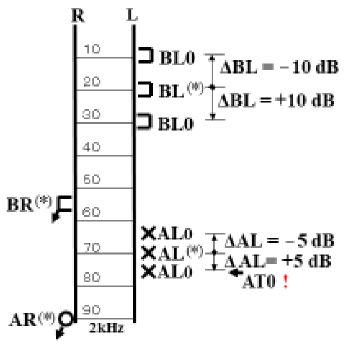

Figure 0-2 Measurement errors

$AL^{(*)}$: Left ear’s true AC threshold in PTA
AL^*: Left ear’s true AC threshold in measurement ($AL^* = AL^{(*)} + \Delta AL$)
AL0: AC threshold measured in the left ear without masking
ΔAL: Measurement error for the AC threshold in the left ear

**** Further note ****

*) Strictly speaking, the true thresholds in PTA have a margin of error less than 5 dB.
*) The function in **Fig. 0-1** is called Gauss function.

0-3 List of Abbreviations

(1) Output levels of the earphones and vibrators

AT (dB HL): Output level of the air-conduction signals
BT (dB HL): Output level of the bone-conduction signals
N (dB HL): Output level of the air-conduction masking noises, narrow band noise
Nn: n-th masking noise

(2) Hearing threshold levels

The air-conduction threshold (AC threshold) is indicated simply by 'A' and the bone-conduction threshold (BC threshold) is indicated by 'B'. The subscripts 'R' and 'L' refer to right and left. The asterisk (*) denotes 'true', and zero (0) denotes 'without masking.'

AR* (dB HTL): True air-conduction threshold level in the right ear
AL* (dB HTL): True air-conduction threshold level in the left ear
BR* (dB HTL): True bone-conduction threshold level in the right ear
BL* (dB HTL): True bone-conduction threshold level in the left ear
AR0 (dB HTL): Air-conduction threshold measured without masking in the right ear
AL0 (dB HTL): Apparent air-conduction threshold in the left ear
BR0 (dB HTL): Apparent bone-conduction threshold in the right ear
BL0 (dB HTL): Apparent bone-conduction threshold in the left ear

The threshold measured without masking is termed "the apparent threshold". It is determined to be the true or false threshold after estimation of masking

(3) Air-bone gaps (AB gap)

An air-bone gap is the difference between air- and bone- conduction threshold, which is indicated by G. When the measured AC and BC thresholds in one ear are both the true thresholds, the AB gap of that ear is referred to as a true AB gap (G*). The AB gap measured without masking is indicated by an apparent AB gap (G0)

GR* (dB): True AB gap of the right ear, GR* = AR* − BR*.
GL* (dB): True AB gap of the left ear, GL* = AL* − BL*.
GR0 (dB): AB gap measure without masking of the right ear, GR0 = AR0 − BR0.
GL0 (dB): AB gap measure without masking of the left ear, GL0 = AL0 − BL0.

Because GR0 is the between the apparent air- and bone- conduction threshold in the one ear, it is the apparent AB gap.

(4) Interaural attenuation

Interaural attenuation has been used when referring to AC because the interaural attenuation for BC is approximately 0 dB and has thus been assumed to be non-existent. However, in theory, interaural attenuation for both AC and BC issues should be treated equally. In this lecture series, interaural attenuation is indicated by Ia.

IaA (dB): Interaural attenuation for air-conduction signals
IaB (dB): Interaural attenuation for bone-conduction signals

(5) Various quantities

α (dB): Effective quantity of masking; αn = Nn − AR*.
  αn: Effective quantity of masking of the n-th masking noise (Nn, n = 1, 2, 3, …)
β (dB): Effective quantity of overmasking); βn = OM level [n] − BL*.
  βn: Effective quantity of overmasking of the n-th masking noise
ω (dB): Amounts of the AC threshold elevation of the test ear; in patterns [4], [7]
  ωn: Amounts of the AC threshold elevation of the n-th masking noise
θ (dB): Amounts of the BC threshold elevation of the test ear; in patterns [4], [7]
  θn: Amounts of the BC threshold elevation of the n-th masking noise
δ (dB): Difference between IaA and the apparent AB gap
  Lt δ = IaA − GL0, Rt δ = IaA − GR0.

(6) Abbreviations

The bellows are all the abbreviations at some frequency.

- AA gap (dB): Difference between the apparent air-conduction thresholds of both ears
- AC: Air conduction
- AC threshold (dB HTL): Air-conduction hearing threshold
- ALn (dB HTL): AC threshold measured with the n-th masking noise (n = 0, 1, 2, …)
- AL0 (dB HTL): Apparent air-conduction threshold in the left ear
- AL* (dB HTL): True air-conduction threshold level in the left ear
- AOB gap (dB): Air and opposite bone gap
- AR0 (dB HTL): Air-conduction threshold measured without masking in the right ear
- AR* (dB HTL): True air-conduction threshold level in the right ear
- AT (dB HL): Air-conduction test signal
- BC: Bone conduction
- BC threshold (dB HTL): Bone-conduction hearing threshold
- BLn (dB HTL): BC threshold measured with the n-th masking noise (n = 0, 1, 2, …)
- BL0 (dB HTL): Apparent bone-conduction threshold in the left ear
- BL* (dB HTL): True bone-conduction threshold level in the left ear
- BR0 (dB HTL): Apparent bone-conduction threshold in the right ear
- BR* (dB HTL): True bone-conduction threshold level in the right ear
- BT (dB HL): Bone-conduction test signal
- CH: Cross hearing
- CH-level (dB HL): Cross-hearing level
    - AL-CH level [0]: CH level for air conduction of the left ear without masking
    - BL-CH level [0]: CH level for bone conduction of the left ear without masking
- CL (dB): Conduction loss
- EML (dB HL): Effective masking level
- GR0 or GL0 (dB): Apparent AB gap of the right or left ear
- GR* or GL* (dB): True AB gap of the right or left ear
- Ia (dB): Interaural attenuation
- IaA (dB): Interaural attenuation for air-conduction signals
- IaB (dB): Interaural attenuation for bone-conduction signals
- MA (dB): Masking amount (the amount of the threshold elevation of the non-test ear)
- mBR[n] (dB HTL): Bone-conduction hearing threshold level masked with the masking noise of Nn in the right, non-test ear
- min BL* (dB HTL): Minimum level of the true BC threshold possible in the left ear
- M level (dB HL): Masking level
- MN (dB HL): Maximum level of masking noise at which overmasking does not occur
- MNnpo (dB HL): Maximum level of masking noise that has no possibility of overmasking
- N (dB HL): Air-conduction noise, or masking noise
- Nmax (dB HL): Maximum adequate masking noise level
- Nmin (dB HL): Minimum adequate masking noise level
- OM: Overmasking
- OMA (dB): Overmasking amount: the amount of the threshold elevation of the test ear
- OM level (dB HL): Overmasking level
- omBL[n] (dB HTL): Bone-conduction hearing threshold level overmasked with the masking noise of Nn in the left, test ear
- omAL[n] (dB HTL): AC threshold overmasked with Nn in the left, test ear
- PW (dB): Plateau width
    - APW: Air-conduction plateau width BPW: Bone-conduction plateau width
- SH: Shadow hearing
- SHT: Shadow-hearing threshold
- SNC (dB): Relative amounts of sensorineural **c**omponent in the right ear
    - Rt SNC = BR* − BL* = Lt MN − Rt MN (≥ 0 dB).
- Y (dB): Amount of physical change

(7) Various noise levels

• **MN** (dB HL): Maximum level of masking noise at which overmasking does not occur
Rt MN = BL* + IaA. (BL*: the true BC threshold in the left, test ear)
It is determined when the true BC threshold in the test ear (BL*) and the IaA value have been obtained (cf. Lecture 2).

• **Nmax** (dB HL): Maximum adequate masking noise level
Rt Nmax = BL* + IaA. (BL*: the true BC threshold in the left, test ear)
It is determined when the plateau width in the test ear has been obtained.
Although Nmax is the same equation as MN, it has different meanings.
If a plateau is present, Nmax = MN.
If no plateau is present, Nmax is absent. However, MN might be present (cf. Lecture 3).

• **Nmin** (dB HL): Minimum adequate masking noise level
Rt ANmin: Minimum adequate masking noise level for air conduction in the right ear
Rt ANmin = AL* − IaA + GR*.
Rt BNmin: Minimum adequate masking noise level for bone conduction in the right ear
Rt BNmin = BL* − IaB + GR*.
In atypical plateau cases, Nmin is either not present or cannot be defined. Therefore, the noise of the level that is equal to the true AC threshold level in the non-test ear is used (cf. Lecture 3).

• **MNnpo** (dB HL): Maximum level of masking noise that has no possibility of overmasking
Rt MNnpo = ALn-1. (AR0 < AL0, Lt AOB gap > 40 dB)
It is determined when the minimum level of the true BC threshold possible in test ear with masking noise of Nn (min BL*n) and the minimum value of IaA or confirmed value have been obtained (cf. Lecture 5).

• **Nx** (dB HL): Maximum level of masking noise at which OM does not occur in any case, assuming the minimum IaA value of 40 dB.
Rt Nx = BL0 + min IaA. (BL0: the BC threshold measured in the left ear without masking)
It is determined when neither the true BC threshold in the test ear (BL*) nor the IaA value have been obtained (cf. Lecture 5).

Lecture 1: Transmission pathways and signal attenuation

In this lecture, sound pressure changes in transmission pathways are considered from three viewpoints: physical, relative, and hypothetical. If we hypothesize that the sound pressures of signals do not change in normal AC and direct BC pathways, then it can be assumed that the signals are relatively attenuated by certain amounts (IaA, IaB, or CL) in the pathways. Therefore, the levels of test signals (AT, BT) at each cochlea are termed hypothetical cochlear levels:

Hypothetical cochlear level [AT] in the cross-converted BC pathway = AT − IaA,
Hypothetical cochlear level [BT] in the cross BC pathway = BT − IaB, and
Hypothetical cochlear level [AT] in the AC pathway [n] = AT − CLn.

In these formulae, AT and BT are AC and BC test signals, respectively. IaA and IaB are the interaural attenuation for the AC and BC signals, respectively. CL is an air conduction loss. When the hypothetical cochlear level of a test signal in one ear is equal to the true BC threshold level in the same ear, the signal is barely heard in the cochlea. Hence, the issue of masking can be discussed based on a common understanding, by simplifying the hearing of signals in this manner.

1.1 Signals transmission pathways to the cochlea

1.1-1 Transmission pathways

(1) Air- and bone-conduction signals
(2) Five transmission pathways

1.1-2 Two phenomena in the cross BC pathway

(1) Cross-hearing phenomenon
(2) Masking phenomenon

1.1-3 Cochlear levels and physical sound pressure changes

1.1-4 Hearing of signals and cochlear levels

1.2 Attenuation in transmission pathways

1.2-1 Air conduction loss: CL

(1) Physical amounts of sound pressure changes for AC signals
(2) Definition of an air conduction loss
(3) CL value calculation
(4) Hypothetical cochlear levels of AC signals in AC pathways

1.2-2 Interaural attenuation for BC signals: IaB

(1) The physical IaB value
(2) Definition of IaB
(3) Calculation of the IaB value
(4) Hypothetical cochlear levels of BC signals in BC pathways

1.2-3 Interaural attenuation for AC signals: IaA

(1) The physical IaA value
(2) Assumption of AC signal attenuation and definition of IaA
(3) Calculation of the IaA value
(4) Hypothetical cochlear levels of AC signals in cross-converted BC pathways

1.2-4 The relative attenuation values in pure tone audiometry: IaA, IaB, CL

1.3 Levels and amounts

(1) Concept of levels and amounts
(2) Physical amounts of sound pressure change
(3) Relative amounts of sound pressure change and hypothetical cochlear levels
(4) Concept extension

1.4 The relationship between an AB gap and IaA

1.5 Masking Diagram

1.6 Summary of Lecture 1

1.1 Signal transmission pathways to the cochlea

1.1-1 Transmission pathways

(1) Air- and bone-conduction signals

The signals used in clinical audiometry are artificial sounds that are generated by transmitters such as supra-aural earphones and bone vibrators. These consist of AC signals (i.e., AC test signals and AC noises) and BC signals (i.e., BC test signals and BC noises).

AC signals reach a cochlea of the participant via its external and middle ear sound-conduction system, which is called an AC transmission pathway (hereafter, AC pathway) (**Fig. 1-1**). By contrast, bone vibrators vibrate the participant's skull to generate a BC signal that travels through the cranium and arrives at the cochlea directly (not via the AC pathway). This is called a BC transmission pathway (hereafter, BC pathway). When a bone vibrator is placed at the mastoid of one ear, the pathway to that ear is termed a direct BC pathway and that to the opposite ear is termed a cross BC pathway. When the bone vibrator is placed at the forehead, the direct BC pathway is equal to the cross BC pathway because the anatomical structure of the cranium is bilaterally symmetrical.

Supra-aural earphones vibrate the participant's skull to generate a BC signal corresponding to the output level of the AC signal. As a result, the BC signal from a supra-aural earphone reaches both cochleae in the same manner as the BC signal from a bone vibrator, which means the supra-aural earphone can also function as a bone vibrator. The BC signal produced by the BC output of a supra-aural earphone, which is tentatively called a converted BC signal (cf. **1.2-3** **[2]**, **Supplement 1**), is transmitted to both cochleae via the BC pathways. The BC pathways of converted BC signals are termed converted BC pathways in order to differentiate them from those of original BC signals (**Fig. 1-1**).

The test signals are AC test signals (AT) and BC test signals (BT). The hearing threshold for AT is the AC threshold, while that for BT is the BC threshold. The test signals are pure tones, and the AC masking noise (N) usually consists of narrow-band noise. Therefore, the converted BC signals consist of converted BC test signals from the AT and converted BC noise from the N.

(2) Five transmission pathways

Signals reach each cochlea through five transmission pathways (**Fig. 1-2**).

1) The AC pathway	(AT, N)
2) The direct-converted BC pathway	(AT, N)
3) The direct BC pathway	(BT)
4) The cross BC pathway	(BT)
5) The cross-converted BC pathway	(AT, N)

The AC signals (AT and N) reach the cochlea in one ear not only via the AC pathway but also via the direct-converted BC pathway in the form of converted BC signals. This direct-converted BC pathway creates the key used to open the black box of masking.

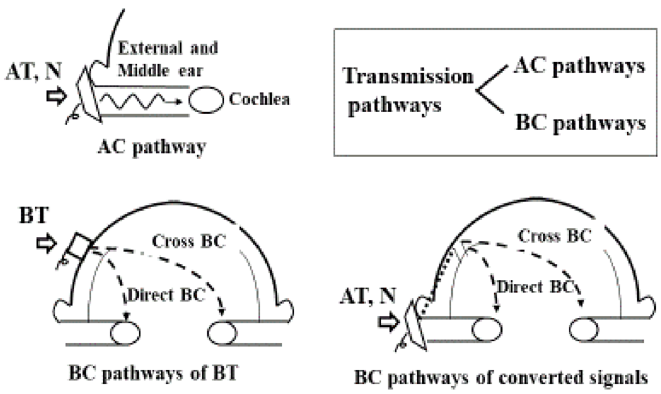

Figure 1-1 Transmission pathways

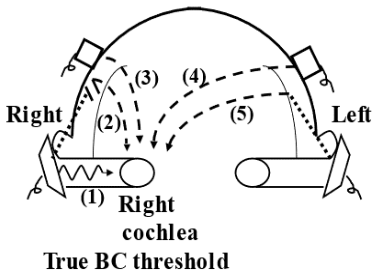

Figure 1-2 Five pathways

**** Further note ****

*) The AC pathway: Trans-tympanic transmission pathway
The direct BC pathway: Trans-temporal transmission pathway
The cross BC pathway: Trans-cranial transmission pathway

1.1-2 Two phenomena in the cross BC pathway

Now, let us consider a hypothetical case in which only the direct BC pathway of the BC signal and AC pathway are present (**Fig. 1-3**). For example, if a participant responds by hearing the test signal presented to the left ear, we can unconditionally determine that it is a true hearing in the left ear. In this case, only the output levels of the test signals may be considered. However, in fact, the situation is quite different because two types of cross BC pathways are present (i.e., the cross BC and cross-converted BC pathways). Therefore, in order to obtain a good viewpoint, two phenomena that occur in these cross BC pathways must be examined, as outlined below.

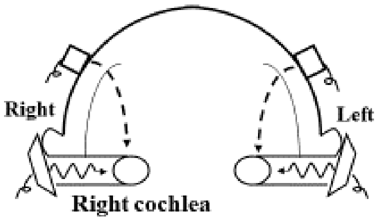

Figure 1-3 Hypothetical case

(1) Cross-hearing phenomenon

The signals (AT, BT, and N) delivered to one ear are heard by the opposite inner ear (cochlea) via the cross and cross-converted BC pathways. This is termed the cross-hearing phenomenon. To illustrate this, let us consider an example in which the right ear is essentially normal, and the left ear is completely deaf. When we examine an AC and BC audiometry without masking, the audiogram presented in **Fig. 1-4** is obtained. Although the left ear is completely deaf, its AC and BC hearing acuity levels appear to be present in the results.

This is because the test signals presented to the left ear are received by the opposite, right inner ear. When the test signals (AT, BT) reach the non-test inner ear via these cross BC pathways and are heard by that ear, what occurs is cross-hearing of the test signals (**Fig. 1-5**). In particular, when the test signal is not heard by the test inner ear, but is heard by the non-test ear, then cross hearing is termed shadow hearing (SH) of the test signal (cf. **2.1-1**). The measured threshold is an SH threshold.

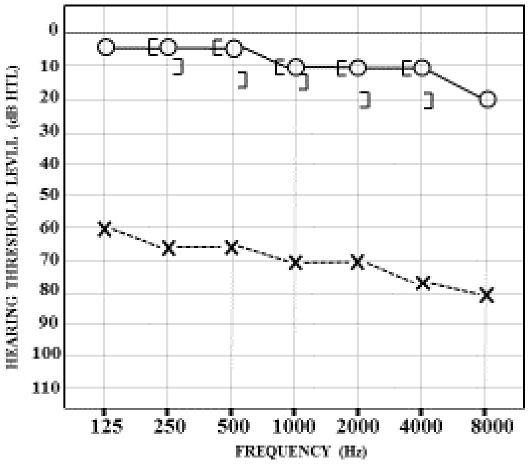

Figure 1-4 Audiogram without masking

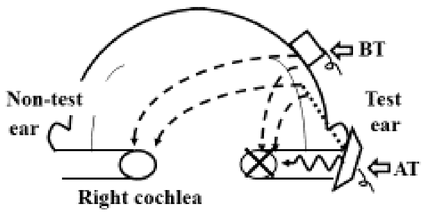

Figure 1-5 Shadow hearing

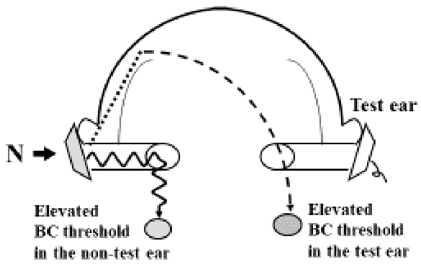

Figure 1-6 Overmasking

(2) Masking phenomenon

The masking phenomenon occurs when the BC threshold of one ear (the test or non-test ear) is elevated due to the presence of masking noise (**Fig. 1-6**). When the AC masking noise (N) reaches the non-test inner ear via the AC pathway and the BC threshold in that ear is elevated, effective masking occurs (cf. **2.2-1**). Simultaneously, the noise reaches the opposite test inner ear via the cross-converted BC pathway (**Fig. 1-6**).

In the case in which the test, left ear is completely deaf (**Fig. 1-5**), no problem occurs because the noise cannot be heard in the test inner ear. However, if some level of BC hearing acuity is retained in the test ear, the noise is perceived by the test inner ear (i.e., cross-hearing of the masking noise), and the BC threshold in the test ear can be elevated. This phenomenon is termed overmasking (cf. **2.3-1**). Therefore, overmasking is both a cross-hearing phenomenon and a masking phenomenon.

**** Further note ****

*) Overmasking is referred to as cross-masking (British Society of Audiology).

1.1-3 Cochlear levels and physical sound pressure changes

When signals (test signals and masking noises) introduced into one ear reach the cochlea of that ear, the sound pressures in the transmission pathways are physically changed (i.e., attenuated or amplified) by certain amounts (**Fig. 1-7**). In response to the output level of a signal (decibel hearing level: dB HL), the level of the signal that has reached the cochlea (i.e., the level of intensity at the cochlea) is called a cochlear level (dB HL). At that point, the difference between the cochlear and output levels is defined as the physical amount of sound pressure change: Y (dB):

Y (dB) = Cochlear level (dB HL) − Output level (dB HL). - - - (1)

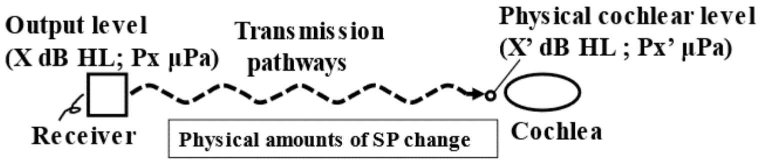

Figure 1-7 Physical sound pressure changes in transmission pathways

The physical amount of sound pressure change (Y) is a physical quantity specific to the transmission pathways. A minus (−) sign means attenuation, while a plus (+) sign means amplification (**Fig. 1-8**). For example, when the sound pressure of the test signal decreases by one hundredth (i.e., the rate of change = 1/100) in a certain pathway, Y is −40 dB, which indicates sound pressure attenuation. Similarly, when it increases tenfold (i.e., the rate of change = 10), Y is +20 dB, which indicates sound-pressure amplification.

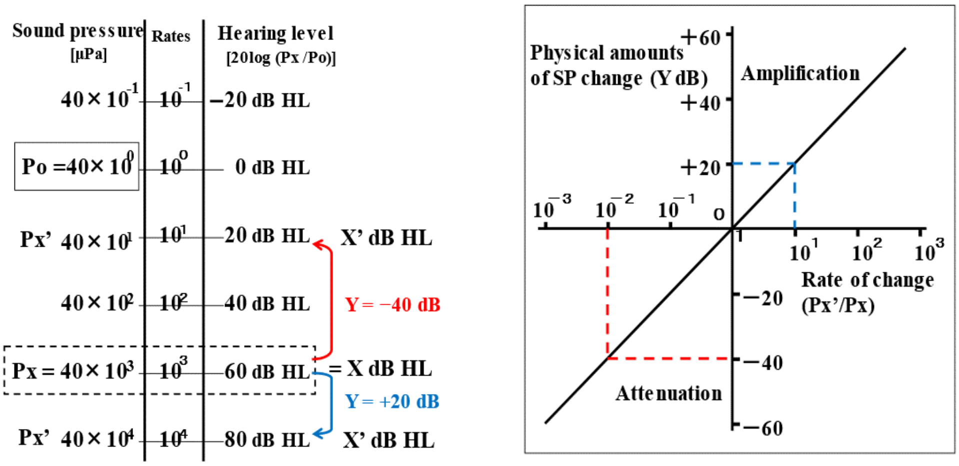

Figure 1-8 Hearing levels and physical amounts of sound pressure change

Based on equation (1), the physical cochlear level can be described as follows:

Physical cochlear level (dB HL) = Output level (dB HL) + Y (dB).

For instance, when an AC test signal (AT) is 60 dB HL and Y1 in one pathway is −40 dB (attenuation), the physical cochlear level of the AT in that pathway is as follows (**Fig. 1-9 [a]**):

Physical cochlear level [AT] = AT + Y1 = 60 (dB HL) + (−40) (dB)
= 20 dB HL.

When AT is 60 dB HL and Y2 in another pathway is +10 dB (amplification) (**Fig. 1-9 [b]**):

Physical cochlear level [AT] = AT + Y2 = 60 (dB HL) + (+20) (dB)
= 80 dB HL.

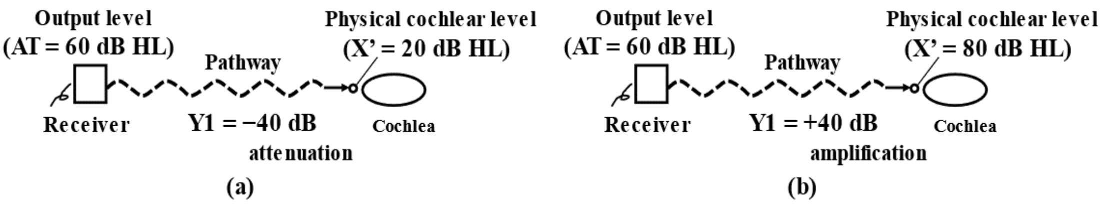

Figure 1-9 Output levels and physical cochlear levels

**** Further note ****

*) When the sound pressure is not changed (Y = 0 dB), the case is included in attenuation for descriptive purposes.

1.1-4 Hearing of signals and cochlear levels

When considering problems related to masking, it is important to know which inner ear "hears" or "does not hear" the signals (test signals and noises) (**Fig. 1-10**). In other words, the signal level at the cochlea is more important than the signal output level. In this lecture series, we stipulate the viewpoint that "the signals are heard by the inner ear or cochlea." Therefore, when the AC test signal reaches the test inner ear (cochlea) via the AC pathway and is barely heard by that inner ear, the hearing of the test signal by the test ear is the true AC hearing, and the measured AC threshold is a true AC threshold. The same holds true for the BC test signal.

In contrast, in cases where the AC/BC test signals presented to the test ear are received by the opposite (non-test) inner ear via the cross and cross-converted BC pathways, the hearing of the test signals by the none-test ear is determined to be the cross hearing of the test signals. The same holds for the AC masking noise.

As a matter of course, even if sounds reach an inner ear, they are not always heard by the inner ear, which is why a determination of whether the presented sounds are heard or not depends on the cochlear level and hearing acuity of that inner ear.

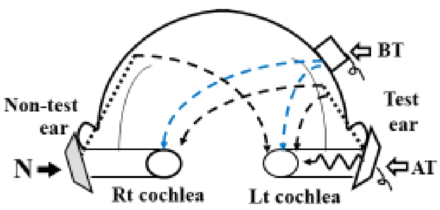

Figure 1-10 Hearing of the test signals and AC masking noise

Although output levels (X dB HL) can be strictly determined physically, in practice it is impossible to measure physical cochlear levels (X' dB HL), which means the physical amount of sound pressure change (Y) is also not measurable. For example, as shown in **Fig. 1-11 (a)**, when AC/BC test signals (e.g., AT of 0 dB HL and BT of 0 dB HL) are directed into a normal hearing ear (e.g., the right ear), they are barely perceptible by the participant. Then, the true AC threshold in the right ear (AR*) is 0 dB HTL, and the true BC threshold in the right ear (BR*) is 0 dB HTL. However, at this time, we cannot know the physical amounts of sound pressure changes and physical cochlear levels in the direct BC and normal AC pathways clinically.

Now, the question arises, "how should we deal with the cochlear level?" This is a focal point of Lecture 1.

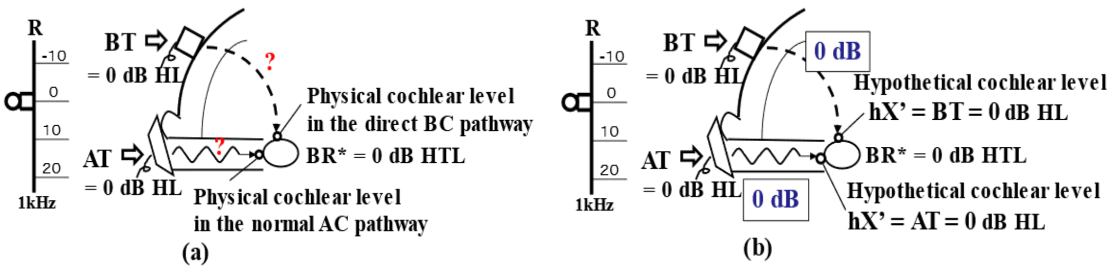

Figure 1-11 Assumptions of the normal hearing ear and hypothetical cochlear levels

The simplest approach is to assume that, in an AC pathway with no conductive disorders (i.e., a normal AC pathway) and a direct BC pathway, the sound pressures of signals do not change (**Fig. 1-11 [b]**). Then it can be assumed that the sound pressures of the AC and BC test signals are neither amplified nor attenuated in either of the pathways, and reach the cochlea at their original sound pressures. Since the cochlear levels are hypothetical, they are termed hypothetical cochlear levels (hX'). It does not matter if we assume the sound pressure change (hereafter, SP change) in this way, because pure tone audiometry is an examination that deals primarily with the issue of whether the signals are heard or not.

Next, we will consider SP changes in impaired AC and cross BC pathways.

**** Further note ****

*) The physical cochlear level (X') in **Fig. 1-11 (a)** is a real level. By contrast, the hypothetical cochlear level (hX') in **Fig. 1-11 (b)** is an unreal level.

1.2 Attenuation in transmission pathways

1.2-1 Air conduction loss: CL

The SP change in the AC pathway is first discussed physically and then considered relatively.

(1) Physical amounts of sound pressure changes for AC signals

An AC test signal (AT) reaches a cochlea via the AC pathway. In a normal AC pathway with no conductive disorders, the sound pressure is physically amplified by approximately +27 dB by means of the external and middle ear amplification mechanism. For simplicity, the amplification value or physical amount of SP change (Y0) is assumed to be just 27 dB.

Fig. 1-12 (a) shows a right ear with a normal AC pathway (i.e., the AC pathway [0]) and a true BC threshold (BR*) of 10 dB HTL. When an AT of 10 dB HL is introduced to this ear, the participant will barely hear it. At this time, the AC signal is physically amplified by +27 dB, and the physical cochlear level in the AC pathway [0] (X0') is as follows:

X0' = AT + Y0 = 10 (dB HL) + 27 (dB) = 37 dB HL.

Therefore, it can be said that when the physical cochlear level [AT] in any AC pathway is 37 dB HL, the AT will be barely heard by an inner ear that has a true BC threshold of 10 dB HTL.

By contrast, **Fig. 1-12 (b)** presents an impaired AC pathway in which the sound pressure is physically amplified by only +7 dB (i.e., the AC pathway [1]), and an AT of 10 dB is not audible in the inner ear. When an AT of 30 dB HL is presented, the physical cochlear level in the AC pathway [1] (X1') is as follows:

X1' = AT + Y1 = 30 (dB HL) + 7 (dB) = 37 dB HL.

At that point, the AC test signal is just audible in the inner ear (BR* = 10 dB HTL).

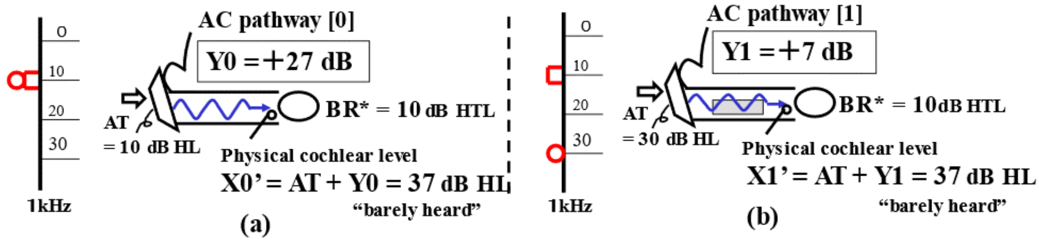

Figure 1-12 Physical amounts of SP change (Yn) and physical cochlear levels (X')

(2) Definition of an air conduction loss

In the AC pathway [1], we can assume that the sound pressure of an AC signal is attenuated by 20 dB relative to a normal AC pathway (**Fig. 1-12**). This 20 dB relative attenuation value represents the extent of a disorder in the sound-conduction system of the external and middle ear and is therefore termed an air conduction loss (CL). Namely, a CL is defined as the relative amount of SP change for AC signals in some AC pathway in relation to a normal AC pathway. The air conduction loss in the AC pathway [n] (CLn) is given by

CLn = Yn − Y0, (n = 0, 1, 2, …),

where Yn and Y0 are the physical amount of SP change in AC pathway [n] and AC pathway [0], respectively. For example, CL0 is 0 dB (**Fig. 1-13 [a]**) and CL1 is −20 dB (**Fig. 1-13 [b]**). Hence, the physical cochlear level in the AC pathway [n] (Xn') may be written as

Xn' = AT + Yn = AT + (Y0 + CLn).

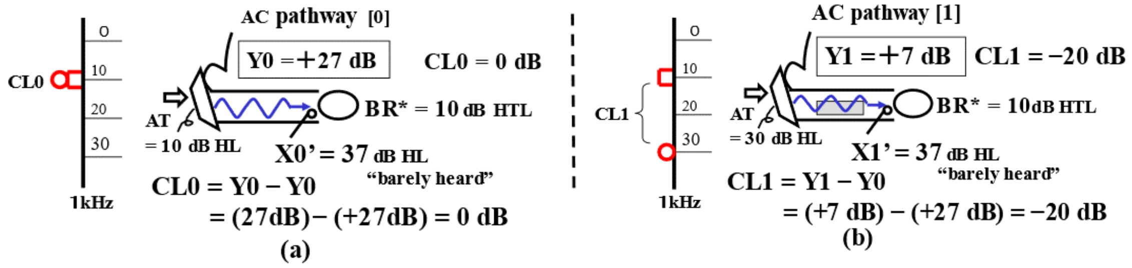

Figure 1-13 Definition of CL

**** Further note ****

*) the amount of conductive disorder in the AC pathway [1] appears on the audiogram as the right AB gap.

*) Complete impedance matching is not accomplished by means of the amplification mechanism. The important thing is that an AC signal of 0 dB HL does not reach the cochlea as the original level (0 dB HL).

(3) CL value calculation

The CLn values are calculated as follows:

The AC pathway [0]: Y0 = +27 dB (amplification); CL0 = Y0 − Y0 = +27 dB − (+27 dB) = 0 dB.
The AC pathway [1]: Y1 = +7 dB (amplification); CL1 = Y1 − Y0 = +7 dB − (+27 dB) = −20 dB.
The AC pathway [2]: Y2 = −3 dB (attenuation); CL2 = Y2 − Y0 = −3 dB − (+27 dB) = −30 dB.

CL values are always attenuation values because they are always less than or equal to 0 dB (CLn ≤ 0 dB). Since the absolute value of CLn appears on the audiogram as the AB gap, it can be obtained as the following equation: **CL = AR* − BR***.

(4) Hypothetical cochlear levels of AC signals in AC pathways

To simplify the discussion, we hypothesize that the sound pressures of AC signals are not changed in the normal AC pathway. More specifically, the hypothetical amount of SP change in the AC pathway [0] (hY0) is assumed to be 0 dB (hY0 = 0 dB) (**Fig. 1-14 [a]**). Under this virtual setting, the hypothetical cochlear level in the AC pathway [n] (hXn’) is written as follows:

hXn’ = AT + (hY0 + CLn)
= AT + CLn.

Hence, the AC signals can be assumed to be changed (i.e., attenuated) by CLn in the AC pathway [n] (i.e., hYn = CLn). For instance, if an AT of 10 dB HL reaches the cochlea without attenuation via the AC pathway [0] (CL0 = 0 dB) and is barely heard by that cochlea (BR* = 10 dB HTL) (**Fig. 1-14 [a]**), the hypothetical cochlear level in the AC pathway [0] (hX0’) is as follows:

hX0’ = AT + CL0 = 10 (dB HL) + 0 (dB) = 10 dB HL.

As in **Fig. 1-14 (b)**, the hypothetical amount of SP change in the AC pathway [1] (hY1) is equal to CL1 (hY1 = CL1 = −20 dB). Thus, it can be assumed that the AT of 30 dB HL is relatively attenuated by 20 dB in that pathway:

hX1’ = AT + CL1 = 30 (dB HL) + (−20) (dB) = 10 dB HL.

Therefore, it can be said that when the hypothetical cochlear level [AT] in any AC pathway is 10 dB HL, the AT is barely heard by an inner ear with a true BC threshold of 10 dB HTL.

Note that the hypothetical cochlear level is equal to the true BC threshold level.

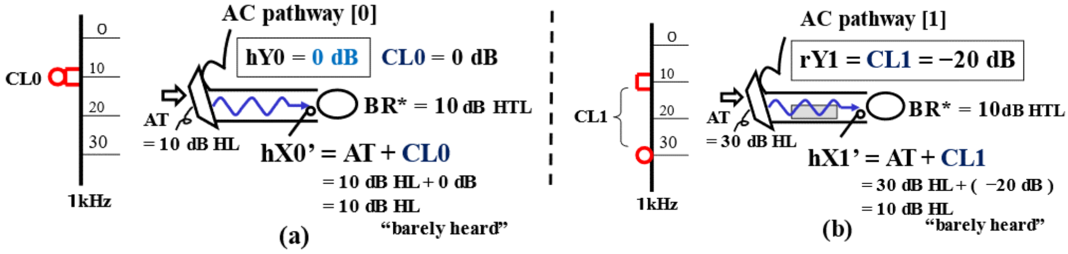

Figure 1-14 Relative amounts of SP change (CLn) and hypothetical cochlear levels (hX’)

Although the sign of CLn is always negative (due to attenuation), the CL value is customarily expressed as its absolute value. For example, as shown in **Fig. 1-15**, a CL1 of 30 dB (= |hY1| = |−30| dB = +30 dB) indicates an attenuation value. Hereafter, CL values representing relative attenuation will be written without a negative sign.

In summary, it can be assumed that AT is attenuated by CLn (≥ 0 dB) in the AC pathway [n] relative to a normal AC pathway. The hypothetical cochlear level of AT in the AC pathway [n] (hXn’) is as follows: **Hypothetical cochlear level [AT] in the AC pathway [n] = AT − CLn.** When this level is equal to the true BC threshold level in that ear, the AT is barely heard.

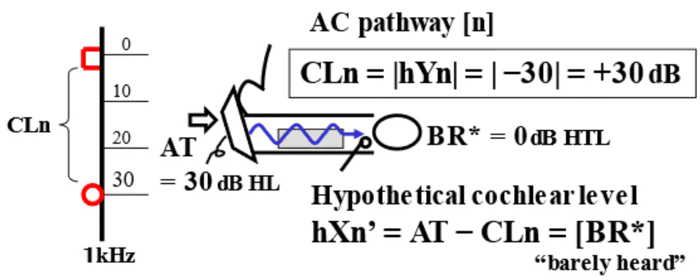

Figure 1-15 CL as its absolute figure

1.2-2 Interaural attenuation for BC signals: IaB

(1) The physical IaB value

Interaural attenuation (Ia) has been defined as "the difference in decibels between the level of the signal at the tested ear and the level at the opposite cochlea" (Yacullo: 1996). According to this definition, the interaural attenuation for BC signals (IaB) can be expressed as follows:

IaB (dB) = Cochlear level [BT] in the cross BC pathway (dB HL) − BT (dB HL),

where BT is a BC test signal (the output level). Therefore, the IaB is the physical amount of SP change for BC signals in the cross BC pathway (**Fig. 1-16**). As described above, since physical cochlear levels are not measurable, the physical amount of SP change (i.e., the physical IaB value) cannot be measured (cf. **1.1-4**). We will consider the definition of IaB in a clinical meaning.

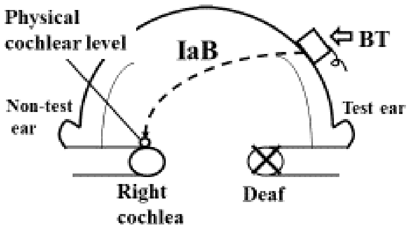

Figure 1-16 Physical IaB

(2) Definition of IaB

Let us examine the interaural attenuation for BC signals when the bone vibrator is placed on the participant's forehead (i.e., IaB at the forehead) (**Fig. 1-17**). It has been explained that the IaB value at the forehead is always 0 dB because both inner ears receive the same BC stimuli. What does this actually mean? Assuming that the physical amounts of SP change in the BC pathways to the right and left cochleae are YR (dB) and YL (dB), respectively, the IaB at the forehead at some frequency is given by

IaB at the forehead = YR − YL.

Here, since the anatomical structure of the cranium is bilaterally symmetrical, YR is always equal to YL (YR = YL). Therefore, the IaB value at the forehead is always 0 dB regardless of the frequencies, participants, or vibrator types used:

IaB at the forehead = YR − YL = 0 dB.

As defined clinically, IaB is the difference between the physical amounts of SP change in both ears. It can be further defined as the relative amount of SP change for BC signals.

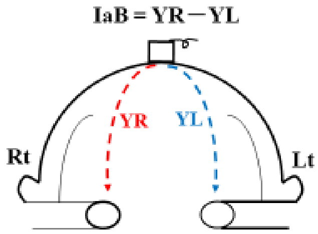

Figure 1-17 IaB at the forehead

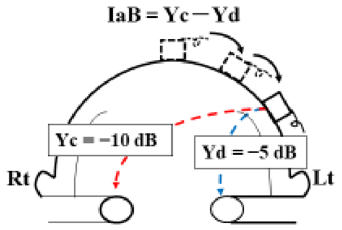

Figure 1-18 IaB at the mastoid

Here, if we gradually move the bone vibrator at the forehead to the left side of the participant's head, we can see that the difference between Y values at both BC pathways (YR − YL) increases (**Fig. 1-18**), until at last the vibrator arrives at the mastoid. The IaB at the mastoid is given by

IaB at the mastoid = Yc − Yd = −10 (dB) − (−5) (dB)
= −5 dB,

where it is assumed that the physical amount of SP change is −5 dB in the direct BC pathway (Yd) and −10 dB in the cross BC pathway (Yc). Consequently, the IaB at the mastoid is defined as the relative amount of SP change for BC signals in the cross BC pathway in relation to the direct BC pathway. Since the sign of IaB is always negative (i.e., Yc ≤ Yd), IaB is a relative attenuation value.

**** Further note ****

*) The value of the IaB at the forehead of 0 dB is derived from the definition. No one has measured the value of 0 dB.

*) Relative amounts of SP change are expressed as rY: Yn − Y0 = CLn, Yc − Yd = IaB.

(3) Calculation of the IaB value

Let us consider the calculation of the IaB value at the mastoid in the participant shown in **Fig. 1-19**. When a BT of 10 dB HL is presented to the right ear, the participant will barely hear it. In this case, the physical cochlear level in the direct BC pathway (Xd') can be represented as follows:

Xd' = BT + Yd = 10 (dB HL) + (−5) (dB) = 5 dB HL.

Therefore, it can be said that when the physical cochlear level of BT is 5 dB HL, the BT is barely heard by an inner ear with a BR* of 10 dB HTL.

Subsequently, when a BT of 15 dB HL is introduced to the left ear, the physical cochlear level in the cross BC pathway (Xc') is as follows:

Xc' = BT + Yc = 15 (dB HL) + (−10) (dB) = 5 dB HL.

At this point, the test signal is just audible in the right inner ear. The BC threshold measured in the left ear without masking (BL0) of 15 dB HTL is the SH threshold, as will be described later (cf. **2.1-2**).

Although the physical amount of SP change cannot be obtained, the relative amount of SP change, i.e., IaB at the mastoid of −5 dB (= Yc − Yd), appears on the audiogram as the difference between both measured BC thresholds, which can be calculated as follows:

IaB at the mastoid = BR* − BL0
= 10 (dB HTL) − 15 (dB HTL)
= −5 dB.

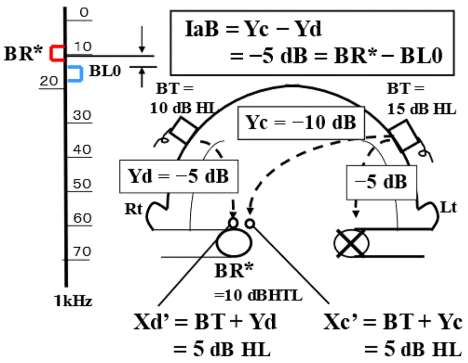

Figure 1-19 Physical cochlear levels

(4) Hypothetical cochlear levels of BC signals in BC pathways

For simplicity, we hypothesize that the sound pressures of BC signals in the direct BC pathway do not change. More specifically, the hypothetical amount of SP change in that pathway (hYd) is assumed to be 0 dB (hYd = 0 dB) (**Fig. 1-20**). Thus, the hypothetical cochlear level of BT in the direct BC pathway (hXd') is as follows:

hXd' = BT + hYd = BT + 0 (dB) = 10 dB HL.

Therefore, it can be said that when the hypothetical cochlear level of BT is 10 dB HL, the BT is barely heard by an inner ear with a BR* of 10 dB HTL.

The hypothetical amount of SP change in the cross BC pathway (hYc) is equal to IaB, as follows:

IaB = Yc − Yd = hYc − hYd = hYc − 0 (dB) = hYc. ∴ **hYc = IaB = −5 dB**.

As with CL, conventionally IaB has been expressed as its absolute value:

IaB = |hYc| = |BR* − BL0| = |10 (dB HTL) − 15 (dB HTL)| = |−5 dB| = +5 dB.

From this point, the IaB represents the relative attenuation value without the negative sign (**Fig. 1-21**).

In summary, it can be assumed that BT is attenuated by IaB (≥ 0 dB) in the cross BC pathway relative to the direct BC pathway. The hypothetical cochlear level of BT in the cross BC pathway (hXc') can be written as

Hypothetical cochlear level [BT] in the cross BC pathway = BT − IaB.

When this level is equal to the true BC threshold level in that ear, the BT is barely heard.

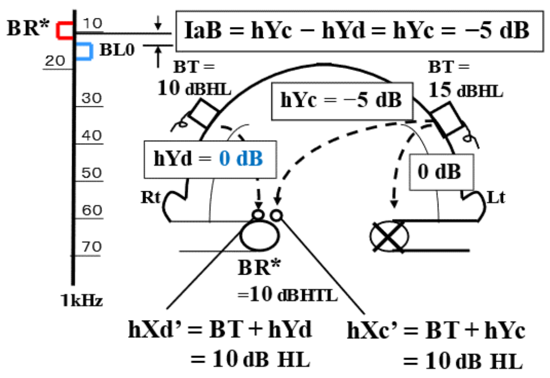

Figure 1-20 Hypothetical cochlear levels

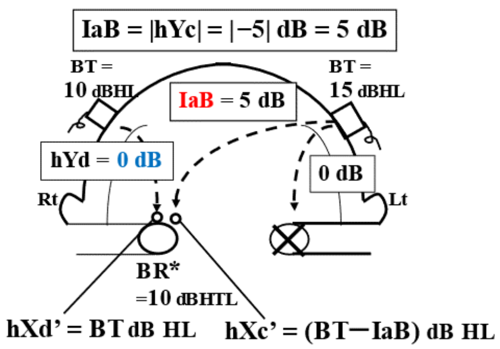

Figure 1-21 IaB as its absolute figure

1.2-3 Interaural attenuation for AC signals: IaA

(1) The physical IaA value

As explained above, supra-aural earphones generate a BC signal corresponding to the output level of the AC signal. (cf. **1.1-1** **[1]**). Based on the classical definition, the interaural attenuation for AC signals (IaA) can be expressed as follows (**Fig. 1-22**):

IaA (dB) = Cochlear level [AT] in the cross BC pathway (dB HL) − AT (dB HL),

where AT is an AC test signal or output level. The IaA has been defined as the physical amount of SP change for AC signals in the cross-converted BC pathway. However, the physical amount of SP change cannot be obtained clinically. The strict definition of IaA is somewhat difficult, therefore this issue will be addressed in **Supplement 1**.

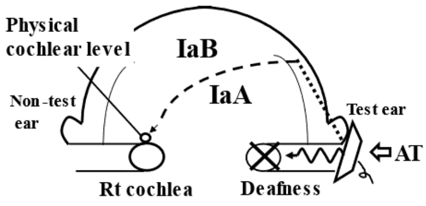

Figure 1-22 Physical IaA

(2) Assumption of AC signal attenuation and definition of IaA

Let us make the following assumption to simplify the theory and make it possible to handle clinical IaA more easily. When AC signals are presented to one ear using supra-aural earphones, the energy (or sound pressure) is attenuated by constant amounts via the cross-converted BC pathway and the AC signals are converted into BC signals. These converted BC signals will eventually reach the opposite inner ear or cochlea. Under this assumption, IaA can be dealt with similarly to IaB. That is, the IaA can be defined as the relative amount of SP change for AC signals in the cross-converted BC pathway in relation to the direct BC pathway (**Fig. 1-23**).

(3) Calculation of the IaA value

The IaA value, which appears on an audiogram as the difference between the measured thresholds (BR*, AL0) (**Fig. 1-24**), can be calculated by the following equation:

IaA = BR* − AL0 = 10 (dB HTL) − 70 (dB HTL) = −60 dB,

where AL0 is the AC threshold measured in the left ear without masking (i.e., the SH threshold). According to customary practice, IaA is expressed as its absolute value. Thus, an IaA of +60 dB is a relative attenuation value.

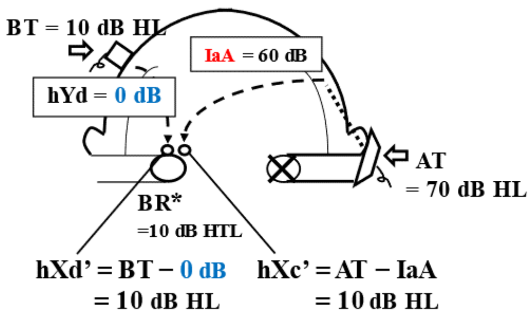

Figure 1-23 Hypothetical cochlear levels

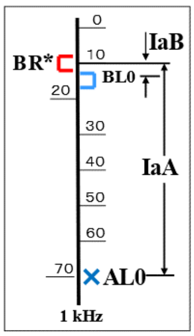

Figure 1-24 Calculation of the IaA value

(4) Hypothetical cochlear levels of AC signals in cross-converted BC pathways

As in **Fig. 1-23**, assuming that the hypothetical amount of SP change in the direct BC pathway is 0 dB (hYd = 0 dB), it can be presumed that when an AT of 70 dB HL is presented to the left ear, it is relatively attenuated by IaA (= 60 dB) in the cross-converted BC pathway before reaching the opposite cochlea. Therefore, the hypothetical cochlear level of AT in that pathway can be written as

Hypothetical cochlear level [AT] in the cross-converted BC pathway = AT − IaA

= 70 (dB HL) − 60 (dB)

= 10 dB HL (= BR*).

Then, an AT of 70 dB HL is barely heard by the right inner ear (BR* = 10 dB HTL).

**** Further note ****

*) To put the assumption plainly, we can proceed as if AC signals are attenuated and become BC signals. In fact, the IaA value is not an attenuation value but should be called a conversion quantity (cf. **Supplement 1**).

*) The precondition for the calculation of the IaA and IaB values is that the occlusion effect does not occur.

1.2-4 The relative attenuation values in pure tone audiometry: IaA, IaB, CL

The relative amounts of SP change in PTA (rY: IaA, IaB, and CL) all show relative attenuation values in transmission pathways in relation to standard pathways. Since these relative attenuation values are equivalent, they can be managed in a unified form.

a) We hypothesize that the sound pressures of signals remain unchanged in the two standard pathways (**Fig. 1-25**) as described below:

The hypothetical amount of SP change in the normal AC pathway: hY0 = 0 dB,

The hypothetical amount of SP change in the direct BC pathway: hYd = 0 dB.

Under the virtual setting, it can be assumed that the signals are relatively attenuated by a certain amount (rY: IaA, IaB, or CL) in the transmission pathways before reaching a cochlea (**Fig. 1-26**). Namely, the hypothetical amounts of SP change can be assumed to be equal to the relative amounts of SP change (hY = rY). These relative attenuation values are customarily expressed as absolute values. The hypothetical cochlear levels of the test signals are as follows (**Fig. 1-27**):

Hypothetical cochlear level [AT] in the cross-converted BC pathway = AT − IaA, Hypothetical cochlear level [BT] in the cross BC pathway = BT − IaB, Hypothetical cochlear level [AT] in the AC pathway [n] = AT − CLn.

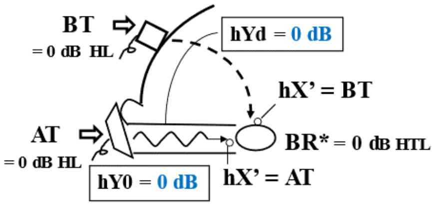

Figure 1-25 Assumptions

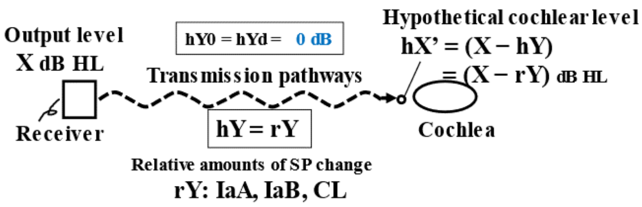

Figure 1-26 Hypothetical SP change (hY = rY)

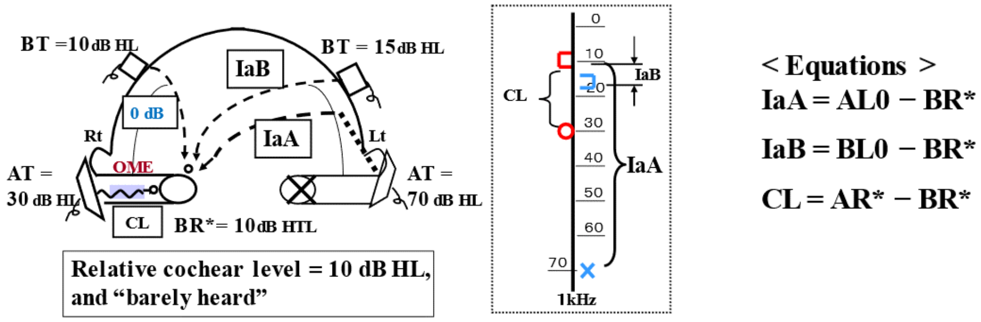

Figure 1-27 Relative attenuation values in pure tone audiometry

b) It can be said that when the hypothetical cochlear level of the test signals in one ear is equal to the true BC threshold level of that ear, the signals are barely heard by the cochlea (**Fig. 1-27**).

Hypothetical cochlear level [the test signal] < the true BC threshold - - - 'not heard'

Hypothetical cochlear level [the test signal] = the true BC threshold - - - 'barely heard'

Hypothetical cochlear level [the test signal] > the true BC threshold - - - 'heard'

These are further generalized as follows:

< The inner ear with the true BC threshold of Z dB HTL > If an inner ear or cochlea has a true BC threshold of Z dB HTL for any given value of Z, and the hypothetical cochlear levels of the signals (test signals, masking noises, or converted BC signals) in that ear are Z dB HL, then the signals can be barely heard by that cochlea. This is true for all cases regardless of the pathways used to reach the cochlea (cf. **1.1-1**).

c) In some cases, the three relative attenuation values (IaA, IaB, and CL) appear on an audiogram as the difference between measured thresholds, as shown in **Fig. 1-27**. More specifically, the IaA and IaB values can be obtained only when the measured AC and BC thresholds in one ear are the SH thresholds, whereas the CL values are measurable when the AC test signals are barely heard via the AC pathway.

**** Further note ****

*) In **Fig. 1-27**, the direct-converted BC pathway is left out. Its significance is addressed in **1.4**.

1.3 Levels and amounts

(1) Concept of levels and amounts

An AB gap is defined as the difference between the AC and BC threshold levels in one ear. The difference between these two levels is defined as "an amount" in this lecture series. In order to distinguish amounts from various levels (dB SPL, dB HL, and dB HTL), amounts are labeled dBy. Typical amounts include interaural attenuation (Ia), air conduction loss (CL), etc. In fact, an effective level is an amount (cf. **2.2-1**).

The levels and amounts correspond to clock times and time amounts, respectively. For example, in the same way that we could say "there are six one-hour differences from 1:00 to 7:00," we may say that "there are 60 differences of 1 dBy from 10 dB HL to 70 dB HL." However, it makes no sense to compare the two. Namely, the expression, "which is larger or higher, 7:00 or six hours?" is meaningless because clock times and time amounts cannot be compared.

Nevertheless, when discussing masking, few people will question statements such as, "the AC threshold of 70 dB HTL is greater or higher than IaA of 60 dBy." This is because levels and amounts have often been confused, which has prevented people from fully understanding the concept of masking. This, in turn, is troublesome because it might lead to errors not only for beginners but also for persons in authority in the field of audiology. Therefore, to describe masking precisely, it is imperative that we make a clear distinction between levels and amounts. Hence, in principle, the comparatives below should be used:

Levels: higher/lower,
Amounts: greater or larger/less or smaller.

(2) Physical amounts of sound pressure change

Since dB is a scale relative to a standard (i.e., a proportion with respect to a standard value), its relationship to the standard must be demonstrated. For example, the reference sound pressure (RSP) used for the dB SPL (sound pressure level) standard is 20 μPa at all frequencies.

For dB HL, the RSP (Po) at 1 kHz is approximately 42 μPa (0 dB HL at 1 kHz = 6.5 dB SPL). For simplicity, assuming that Po at 1 kHz is just 40 μPa, the hearing level (X dB HL) of a certain sound pressure (Px) can be represented as follows:

$$\mathbf{X\ (dB\ HL) = 20\ log_{10}\ (Px/Po)}.$$

For example, 60 dB HL means that the sound pressure is a thousand times the value of Po, which indicates its relative value (**Fig. 1-28**). For that time, it shows the absolute value of 40×10^3 μPa. That is, dB HL is the relative scale (i.e., the relative physical quantity) and presents the absolute physical quantity. In contrast, the dB HTL only presents the relative physical quantity.

Here, for instance, as shown in **Fig. 1-28**, assuming that the reference sound pressure is newly set to 40×1000 μPa (i.e., new Po = Px = 40×1000 μPa, X = 60 dB HL), Px' of 40×10 μPa (X' = 20 dB HL) is the sound pressure decreased by one hundredth, and Px' of 40×10000 μPa (X' = 80 dB HL) is the sound pressure increased tenfold. In this manner, we can provide a given sound pressure with the standard value (new Po = Px, X dB HL) and convert the ratio Px' to Px (the rate of change = Px'/Px) to the hearing level in dB as follows:

$$Y = 20\ log_{10}\ (Px'/Px)$$
$$= 20\ log_{10}\ [(Px'/Po) / (Px/Po)]$$
$$= 20\ log_{10}\ (Px'/Po) - 20\ log_{10}\ (Px/Po)$$
$$\therefore \mathbf{Y\ (dBy) = X'\ (dB\ HL) - X\ (dB\ HL)},$$

where, in this lecture, Y refers to the physical amount of SP change (cf. **1.1-3**) and is represented as the difference between two dB hearing levels. Note that Y (dBy) is only the relative physical quantity, i.e., it is dimensionless. A positive value (Y > 0 dBy) is an amplification, and a negative value (Y < 0 dBy) is an attenuation. When the sound pressure is not changed (Y = 0 dBy), the value is considered attenuation for descriptive purposes.

Additionally, in the operation of levels and quantities (amounts), each term of equality and inequality is represented as a numerical value (cf. **2.4 [1]**).

**** Further note ****

*) In order to demonstrate dB of a relative scale, "dBr" is sometimes used.
*) $20\ log_{10}\ (42\mu Pa / 20\mu Pa) = 20\ log_{10}\ 2.1 = 20 \times 0.322 = 6.44$ dB SPL.
*) An AC test signal of 60 dB HL presents the absolute physical quantity of 40×1000 μPa. In contrast, the IaA value of 60 dBy is the dimensionless quantity with no absolute physical quantity.

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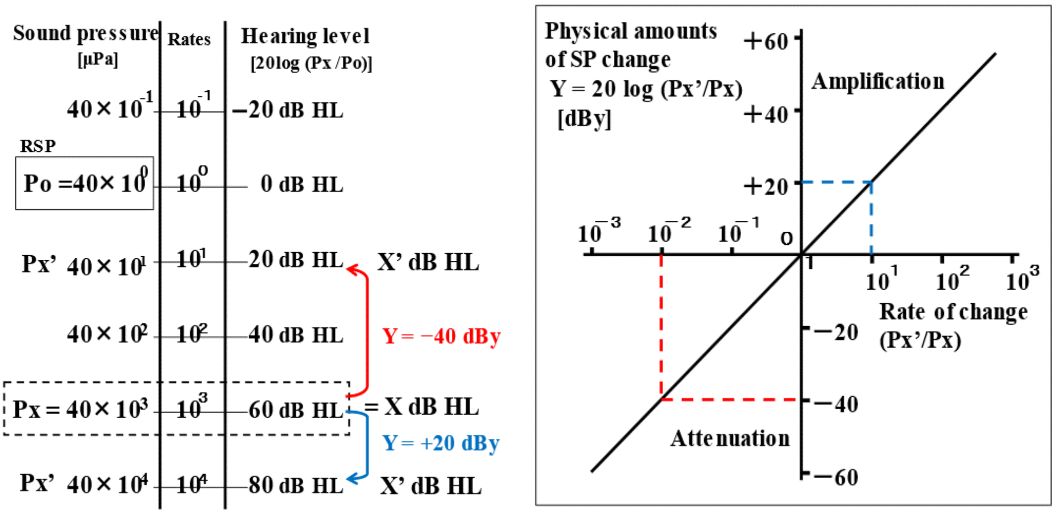


Figure 1-28 Hearing levels (dB HL) and physical amounts of sound pressure change

(3) Relative amounts of sound pressure change and hypothetical cochlear levels

As stated above, if the hypothetical amounts of SP change in normal AC and direct BC pathways are assumed to be 0 dB (hY0 = 0 dB, hYd = 0 dB)), the relative amounts of SP change in the AC and cross BC pathways (rY: IaA, IaB, and CL) can be represented as the differences between the hypothetical cochlear levels (hX') and the output levels of test signals (X: AT and BT) (**Fig. 1-29**, cf. **1.2-4**):

IaA (dBy) = Hypothetical cochlear level [AT] in the cross-converted BC pathway − AT ≤ 0 dB,
IaB (dBy) = Hypothetical cochlear level [BT] in the cross BC pathway − BT ≤ 0 dB,
CLn (dBy) = Hypothetical cochlear level [AT] in the AC pathway [n] − AT ≤ 0 dB,

where all the signs are negative because they are relative attenuation values. However, conventionally, they have been expressed as absolute values (cf. **1-2-1** **[4]**).

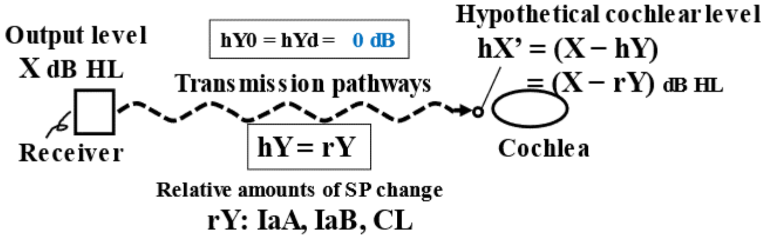


Figure 1-29 Hypothetical SP change (hY = rY)

(4) Concept extension

By extending this approach to cases not involving hearing levels, in this lecture series the differences between various levels (i.e., dB HL and/or dB HTL) are all referred to as "amounts," and the above attenuation values are reflected in the differences between dB HTLs.

IaA (dBy) = the SH threshold for AC (dB HTL) − the opposite true BC threshold (dB HTL),
IaB (dBy) = the SH threshold for BC (dB HTL) − the opposite true BC threshold (dB HTL),
CLn (dBy) = the AC threshold in one ear (dB HTL) − the BC threshold in that ear (dB HTL).

An AB gap and plateau width are as follows:

AB gap (dBy): the AC threshold in one ear (dB HTL) − the BC threshold in that ear (dB HTL),
Plateau width (dBy): Nmax (dB HL) − Nmin (dB HL),

where Nmax and Nmin are the maximum and minimum adequate masking noise levels, respectively. (cf. Lecture 3). Additionally, since the expression for amounts in dB (dBy) is not customary, it will not be used from now on.

**** Further note ****

*) Physical amounts of SP change (Y = X' − X): Y0, Yn, Yd and Yd.
Relative amounts of SP change (rY): CLn = Yn − Y0, IaB = Yc − Yd.
Hypothetical amounts of SP change (hY): hY0 = 0 dB, hYd = 0 dB, CLn = |hYn|, IaB = |hYc|.
It is difficult to represent IaA as a strict equation (cf. **Supplement 1**).

1.4 The relationship between an AB gap and IaA

When an AC test signal is introduced into one ear by supra-aural earphones, the BC output of the earphones generates a converted BC test signal (cf. **1.1-1**) that can reach the cochlea of the same ear via the direct-converted BC pathway. Here, the relative attenuation values in that pathway are assumed to be the same as the IaA value, and cannot be larger than the IaA value in any case. The hypothetical cochlear levels in the AC and direct-converted BC pathways are as follows:

Hypothetical cochlear level [AT] in the AC pathway = AT − CL,

Hypothetical cochlear level [AT] in the direct-converted BC pathway = AT − IaA.

Usually, since amounts of conduction loss are smaller than IaA values (CL < IaA), the hypothetical cochlear level [AT] in the AC pathway is higher than that in the direct-converted BC pathway (**Fig. 1-30 [a]**). As a result, the AC test signal is heard via the AC pathway, and the AB gap is equal to the CL value.

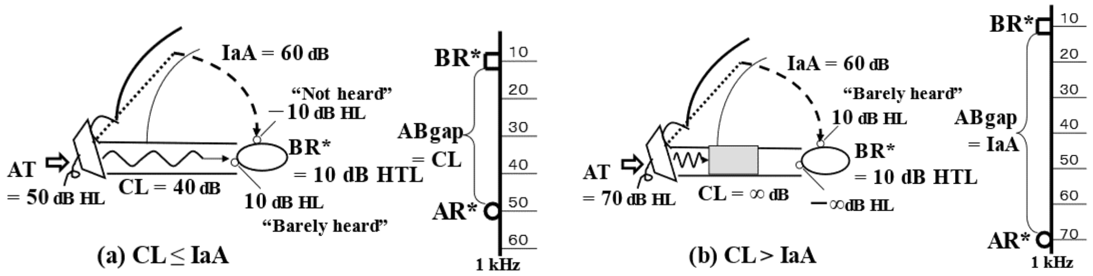


Figure 1-30 Relationship between AB gap and IaA

However, in the case of external ear canal atresia, for example, the CL value is so much larger than the IaA value (CL >> IaA) that the converted BC test signal will be heard via the direct-converted BC pathway (**Fig. 1-30 [b]**). Note that the participant will be unable to tell the difference between the converted BC test signal and the original AC test signal. Therefore, the AB gap at this time is equal to the IaA value. It is because AB gaps are limited to IaA values that the maximum limit of conductive hearing loss is considered approximately 60 dB HTL. Consequently, however severe an air conductive disorder may be, the AB gap at any one frequency is never larger than the IaA value at that same frequency:

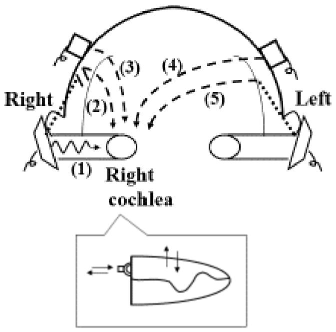
AB gap ≤ IaA.

This relationship appears in almost all phases of problems related to masking. Hence, without considering this relationship, it is almost impossible to explain the fundamental structure of masking in a rational way. Seen from another viewpoint, the reason traditional descriptions of masking are typically impenetrable is that they do not address this relationship. These implications will be discussed in greater detail in Lecture 4.

In short, the AB gap is defined as the difference between the true AC and BC thresholds in one ear. In many cases, the AB gaps are equal to CL values (AB gap = CL) and represent the extent of the disorder in the sound conduction system of the external and middle ear. In only a few cases, AB gaps are equal to IaA values (AB gap = IaA). In other words, AB gaps do not always accurately show the conductive disorder. More specifically, an AB gap is equal to the smaller of the CL and IaA values. It should be noted that the equation AB gap = CL is not always correct.

** Further note **

*) The lamina basilaris vibration: when AC and BC sounds are transmitted to a cochlea via the transmission pathways, the endolymph of the cochlea is oscillated, which causes the lamina basilaris cochlea to vibrate. The traveling waves of the lamina are the same regardless of AC or BC. Specifically, perception of the sounds is the same. Therefore, we cannot distinguish between the AC and BC sounds.



*) AB gaps consist of the true AB gap (the difference between the true AC and BC thresholds) and the apparent AB gap (i.e., the difference between the AC and BC thresholds measured without masking, which are not always the true thresholds). These AB gaps are never larger than the IaA value.

1.5 Masking Diagram

To illustrate the concepts of cross hearing, shadow hearing, and masking visually, a masking diagram is shown in **Fig. 1-31**. The vertical (frequency) axis on the audiogram at a given frequency is divided into the right and left axes. IaA and IaB are indicated by dashed lines between the axes. The AC and BC thresholds are indicated simply by ‘A’ and ‘B’, respectively. The subscripts ‘R’ and ‘L’ refer to right and left, respectively. The asterisk (*) denotes true thresholds, and zero (0) denotes thresholds measured without masking. For example, BL* is the true BC threshold in the left ear and AR0 is the AC threshold measured in the right ear without masking. We must estimate whether measured thresholds are true or false thresholds.

In this lecture series, it is assumed that the right ear is the non-test ear, and the left ear is the test ear. No generality is lost under this assumption. To simplify the discussion, the measured or obtained thresholds are assumed to have no error (i.e., an error of ±0 dB, cf. Lecture 0). Furthermore, since we will not use the physical cochlear level, the hypothetical cochlear level is referred to as simply ‘the cochlear level’ from this lecture onward.

AT0 is the AC test signal that the participant barely hears without masking. For instance, when AT0 of 60 dB HL is introduced to the left ear, the cochlear level of AT0 in the cross-converted BC pathway (the right cochlear level [AT0]) is as follows:

Rt cochlear level [AT0] = AT0 − IaA = 60 (dB HL) − 60 (dB)
= 0 dB HL (= BR* = 0 dB HTL),

where the right is presented as Rt. Since the right cochlear level [AT0] is equal to the true BC threshold level in the right ear (BR*), the AT0 is barely heard by the right cochlea. Therefore, the AC threshold measured in the left ear without masking (AL0) of the 60 dB HTL is an SH threshold. The same holds true for BC test signals. When BT0 of 5 dB HL is presented to the left ear, it is just audible in the right cochlea.

Conventionally, an AC threshold measured without masking has been described as “an unmasked AC threshold.” Here, however, the word “unmasked” is not used. Instead, **we** use the word “apparent” to describe an apparent AC threshold.

< Abbreviations >
AT: Air-conduction test signal (dB HL)
BT: Bone-conduction test signal (dB HL)

AR*: True AC threshold in the right ear
AL*: True AC threshold in the left ear
BR*: True BC threshold in the right ear
BL*: True BC threshold in the left ear

AR0: Apparent AC threshold in the right ear
AL0: Apparent AC threshold in the left ear
BR0: Apparent BC threshold in the right ear
BL0: Apparent BC threshold in the left ear
(The apparent threshold is the threshold measured without masking)

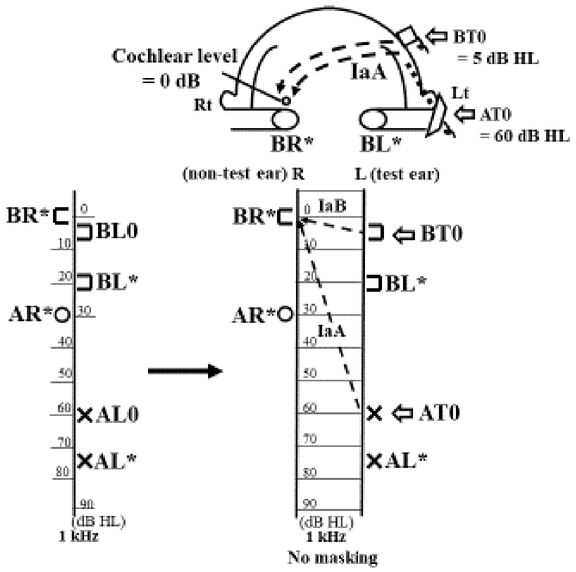


Figure 1-31 Masking Diagram

IaA: Interaural attenuation for air-conduction signals (dB)
IaB: Interaural attenuation for bone-conduction signals (dB)

In this lecture, the three relative attenuation values were considered. In Lecture 2, the three phenomena of shadow hearing, effective masking, and overmasking, will be discussed.

**** Further note ****
*) As AC test signals are elevated from 40 dB HL in 5-dB steps, they are not heard up to 50 dB HL. When AT0 is 60 dB HL, the participant will barely hear it.
*) The masking diagram is based on the figure of König (1963).

1.6 Summary of Lecture 1

1. The signals used in clinical audiometry consist of the AC signals (AC test signals [AT] and masking noises [N]) and the BC signals (BC test signals [BT] and noises). The AC signals reach a cochlea via an AC transmission pathway (AC pathway). When a bone vibrator is placed at the mastoid of one ear, the pathway to that ear is a direct BC pathway and that to the opposite ear is a cross BC pathway. The BC signal generated by the BC output of a supra-aural earphone is called a converted BC signal, which also reach both the inner ears via the direct- and cross-converted BC pathways.

Signals reach each cochlea through five transmission pathways.

1) The AC pathway (AT, N)
2) The direct-converted BC pathway (AT, N)
3) The direct BC pathway (BT)
4) The cross BC pathway (BT)
5) The cross-converted BC pathway (AT, N)

Shadow hearing (SH) of the test signals and overmasking (OM) of the masking noises occur through the cross BC or cross-converted BC pathways.

2. In response to the output level of a signal (dB HL), the level of the signal that has reached the cochlea is called a cochlear level (dB HL). The difference between the cochlear and the output levels is defined as the physical amount of sound pressure (SP) change, Y (dB). Clinically, it is impossible to measure the physical cochlear level and physical amount of SP change.

3. An assumption of AC signal attenuation: when the AC signals are presented to one ear using supra-aural earphones, the energy or sound pressure is attenuated by constant amounts via the direct- and cross-converted BC pathway, and the AC signals are converted into BC signals. These converted BC signals will reach both inner ears.

4. IaA, IaB and CL are defined as follows: The interaural attenuation for AC signals (IaA) is the relative amounts of SP change for AC signals in the cross-converted BC pathway in relation to the direct BC pathway. The interaural attenuation for BC signals (IaB) is the relative amounts of SP change for BC signals in the cross BC pathway in relation to the direct BC pathway. The amount of the air conduction loss (CL) is the relative amounts of SP change for AC signals in some AC pathway in relation to the normal AC pathway. The three relative amounts of SP change (IaA, IaB and CL) appear on the audiogram as the difference between measured thresholds at some cases.

5. It is hypothesized that the sound pressures of signals remain unchanged in the two standard pathways (the normal AC and direct BC pathways); i.e., hY0 = 0 dB and hYd = 0 dB. Then, it can be assumed that the signals are relatively attenuated by a certain amount (rY: IaA, IaB or CL) in the transmission pathways before reaching a cochlea. The hypothetical cochlear levels of the test signals (AT, BT) are as follows:

Hypothetical cochlear level [AT] in the cross converted BC pathway = AT − IaA,
Hypothetical cochlear level [BT] in the cross BC pathway = BT − IaB,
Hypothetical cochlear level [AT] in the AC pathway [n] = AT − CLn.

If the hypothetical cochlear level of test signals in one ear is equal to the true BC threshold level of that ear, the signals are barely heard by the cochlea (i.e., the participant will hear them). The hypothetical cochlear level is referred to as simply the cochlear level.

6. We should make a clear distinction between levels and amounts. In principle, the comparative below should be used:

Levels: higher/lower. Amounts: greater or larger/ less or smaller.

7. However severe an air conductive disorder may be, the AB gap at any one frequency is never larger than the IaA value at that same frequency:

$$\text{AB gap} \leq \text{IaA}.$$

This relationship is essential to explain the fundamental structure of masking in a rational way.

8. A masking diagram was devised to illustrate the concepts of cross hearing, shadow hearing, and masking visually.

Lecture 2: Definition of terms

The aim of masking in pure tone audiometry is to obtain true thresholds of the test ear with adequate masking in the non-test ear. Adequate masking means that the non-test ear is masked by a masking noise that does not cause shadow hearing (SH) and overmasking (OM). It should be noted that SH occurs through cross hearing (CH) of the test signals, whereas OM occurs through CH of the masking noises. In this lecture, the theoretical tools used to describe masking issues are made, and related terms are defined.

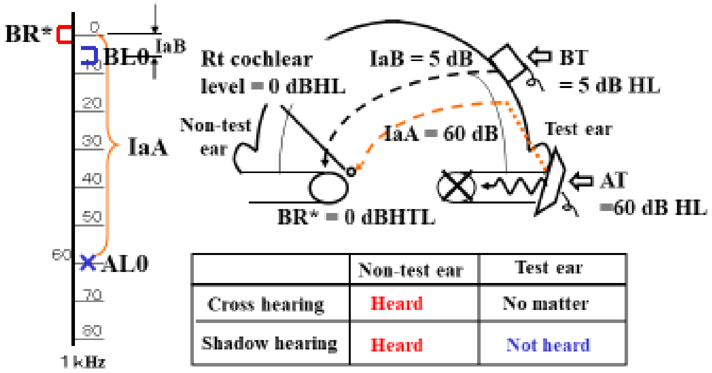
**** Further note ****

) The main abbreviations are listed. AC: Air conduction, BC: Bone conduction, SH: Shadow hearing, CH: Cross hearing, OM: Overmasking, GR: True air-bone (AB) gap in the right ear, GR0: Apparent AB gap in the right ear, IaA: Interaural attenuation for AC signals, IaB: Interaural attenuation for BC signals.

2.1 Shadow hearing

2.1-1 Definition of CH and SH

Although CH and SH have been considered synonymous, they should be distinguished (cf. **1.1-2 [1]**) and are defined as follows (**Fig. 2-1**): CH is defined as hearing the signals (test signals or masking noises) presented to one ear by the opposite inner ear, regardless of whether or not they are heard by the ear to which they are presented. By contrast, SH is defined as hearing the test signals by the non-test inner ear, and not by the test inner ear.



	Non-test ear	Test ear
Cross hearing	Heard	No matter
Shadow hearing	Heard	Not heard

Figure 2-1 Cross hearing and shadow hearing

Let us consider the audiometric configuration at 1 kHz, where the true BC threshold in the right ear (BR*) is 0 dB HTL, the left ear is completely deaf, the IaA value is 60 dB, and the IaB value is 5 dB (**Fig. 2-2[a]**). An AC test signal (AT) is introduced to the participant's left (test) ear.

a) When an AT is 40 dB HL (**Fig. 2-2[a]**), the cochlear level of the right (non-test) ear is as follows:

Rt cochlear level [AT] = AT − IaA = 40 (dB HL) − 60 (dB)
= −20 dB HL (< BR* = 0 dB HTL).

At that point, the test signal is "not heard" by the non-test inner ear (BR*), nor is an AT of 50 dB heard.

b) Especially when an AT0 is 60 dB HL (**Fig. 2-2[b]**), the right cochlear level is as follows:

Rt cochlear level [AT0] = AT0 − IaA = 60 (dB HL) − 60 (dB)
= 0 dB HL (= BR* = 0 dB HTL).

Therefore, the test signal is "barely heard" by the non-test inner ear. Moreover, when an AT is 70 dB HL,

Rt cochlear level [AT] = AT − IaA = 70 (dB HL) − 60 (dB)
= 10 dB HL (> BR* = 0 dB HTL).

It is heard by the non-test inner ear. The same holds true for an AT of 80 dB HL.

c) For BC (**Fig. 2-2[c]**), when a BT0 of 5 dB HL is delivered to the left ear, it is "barely heard" by the non-test inner ear.

Based on the above, a cross-level is defined as shown in the following subsection.

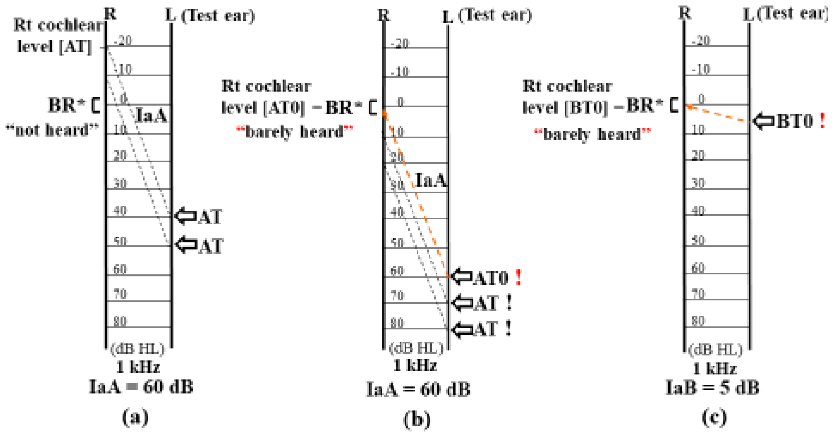


Figure 2-2 Cross hearing of the test signals

**** Further note ****

*) IaA is the interaural attenuation for AC signals. IaB is the interaural attenuation for BC signals.

*) In equations, Rt and Lt represent the right and left, respectively.

2.1-2 CH levels

The minimum hearing level (dB HL) at which CH of the test signals occurs is referred to as the CH level. The CH level provides an indicator used to determine whether the measured thresholds might possibly be SH thresholds.

As shown in **Fig. 2-3 (a)**, without masking, the CH level for AC in the left ear (AL-CH level [0]) that corresponds to the BR* of 0 dB HTL is given by

AL-CH level [0] = BR* + IaA = 0 (dB HTL) + 60 (dB)
= 60 dB HL.

Here, when an AC test signal at a level that is equal to the AL-CH level [0] (i.e., AT0 of 60 dB HL) is presented to the left (test) ear, the right cochlear level [AT0] becomes equal to the BR* (**Fig. 2-3 [a]**, cf. **2.4 [1]**). Therefore, the signal is barely heard by the right (non-test) inner ear (BR*). At that time, whether it can be heard by the test inner ear does not matter. Similarly, the CH-level [0] for BC in the left ear (BL-CH level [0]) is given by

BL-CH level [0] = BR* + IaB = 0 (dB HTL) + 5 (dB)
= 5 dB HL.

When a BT0 of 5 dB HL is directed to the left ear, it is barely heard by the right inner ear.

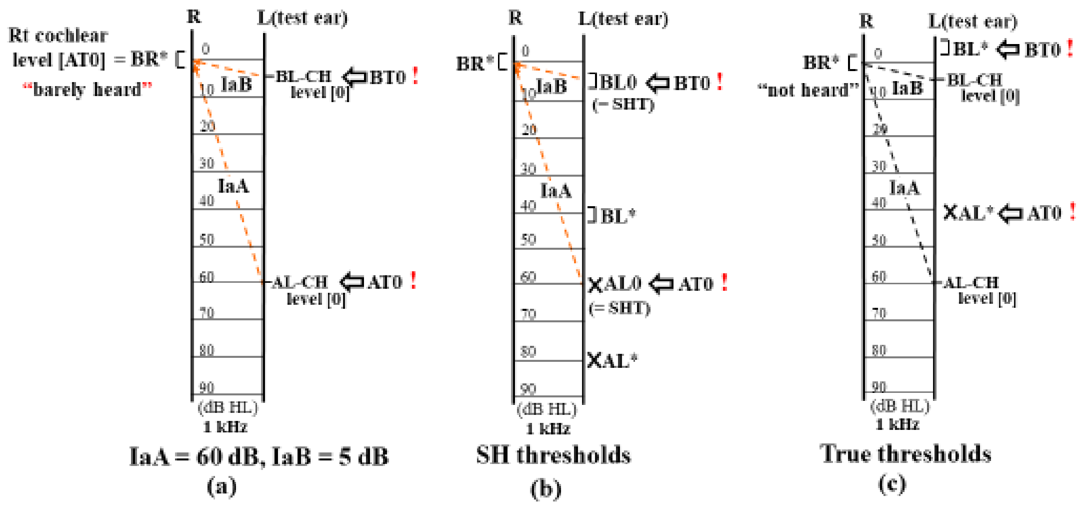


Figure 2-3 CH levels and measured thresholds

Next, **Fig. 2-3 (b)** shows a case where the true AC threshold level in the left ear (AL*) is higher than the AL-CH level [0] (AL* = 80 dB HTL > AL-CH level [0] = 60 dB HL), in which case an AT0 of 60 dB HL is barely heard by the right (non-test) inner ear (BR*) and is not heard by the left (test) inner ear (BL*). Hence, the apparent AC threshold in the left ear (AL0) of 60 dB HTL is an SH threshold. Similarly, for BC, the apparent BC threshold in the left ear (BL0) of 5 dB HTL is the SH threshold because the BL* = 40 dB HTL > BL-CH level [0] = 5 dB HL.

In **Fig. 2-3 (c)**, we can see that when AL* ≤ AL-CH level [0] (AL* = 40 dB HTL < 60 dB HL), the hearing of an AT0 of 40 dB HL is a true hearing and the measured AC threshold (AL0 of 40 dB HTL) is a true hearing threshold. Note that, regardless of level, no AC test signals will cause SH. The same holds true for BC signals.

SH is also known as false hearing. However, true hearing is defined as hearing the test signals by the test inner ear (i.e., the true BC threshold in the test ear). At this time, it does not matter whether or not they are also heard by the non-test inner ear. Note that the true BC threshold in the right (non-test) ear (BR*) becomes the first cause of SH for the test signals.

Additionally, in the operation of levels and quantities (amounts), each term of equality and inequality is represented as a numerical value (cf. **2.4 [1]**).

**** Further note ****

*) The apparent AC threshold in the left ear (AL0) is measured without masking.

*) AT0 is the AC test signal that the participant barely hears without masking, and likewise for BT0 as regards the BC test signal.

*) CH is used for both the test signals and noises. The CH level is limited to the test signals.

*) Lecture 3 will reveal why cross, shadow, and true hearing are defined in this way (cf. **3.1-2 [4]**).

2.1-3 SH thresholds and calculation of the IaA and IaB values

(1) An audiogram without masking

Fig. 2-4 shows an audiogram without masking in which the IaA value at 1000 Hz is larger than or equal to 60 dB (IaA ≥ 60 dB) for the reason described below.

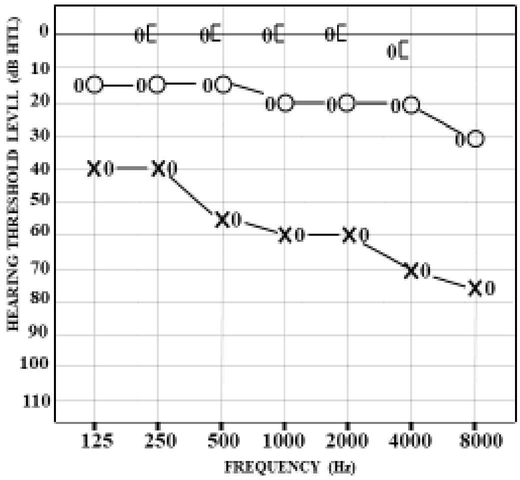


Figure 2-4 Audiogram without masking

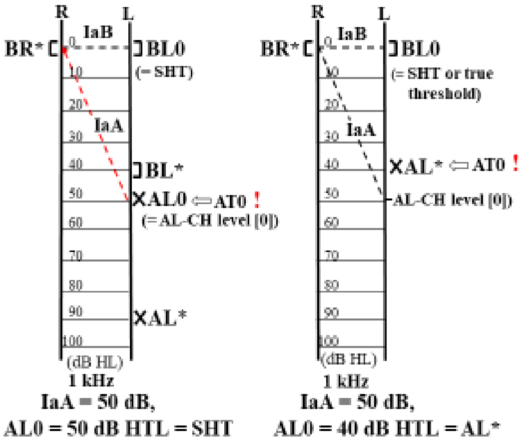


Figure 2-5 IaA = 50 dB

AL* at 1000 Hz is higher than or equal to 60 dB HTL (AL* ≥ 60 dB HTL) because the AL0 of 60 dB HL is either the true or SH threshold. Similarly, the apparent BC threshold in the right ear (BR0) at 1000 Hz is either the true or SH threshold. Let us consider the two cases below:

a) A case where the BR0 at 1000 Hz is the true threshold (BR0 = BR*).

If the IaA value is 50 dB (**Fig. 2-5**), evidently, an AL0 of 60 dB HTL cannot be obtained. Hence, the IaA value at 1000 Hz can never be 50 dB.

If the IaA value is 60 dB (**Fig. 2-6 [a]**, **[b]**),

AL-CH level [0] = BR0 + IaA = 0 (dB HTL) + 60 (dB) = 60 dB HL (= AL0).

Therefore, an AL0 of 60 dB HTL is either the SH or true threshold.

If the IaA value is 70 dB (**Fig. 2-6 [c]**),

AL-CH level [0] = BR0 + IaA = 0 (dB HTL) + 70 (dB) = 70 dB HL (> AL0).

At that point, an AL0 of 60 dB HTL cannot be the SH, but true threshold. Therefore, when BR0 = BR*, the IaA value at 1000 Hz is larger than or equal to 60 dB (IaA ≥ 60 dB).

b) A case where the BR0 at 1000 Hz is the SH threshold (i.e., BR0 < BR*).

As shown in **Fig. 2-7**, since neither AL0 nor BL0 can be SH thresholds, they are always true thresholds. The IaA value must be larger than or equal to 60 dB (IaA ≥ AB gap = 60 dB) because the true AB gap of the left ear is 60 dB.

Consequently, we know that the IaA value at 1000 Hz is larger than or equal to 60 dB. In Lecture 4, we will address this issue as an extremely important masking problem.

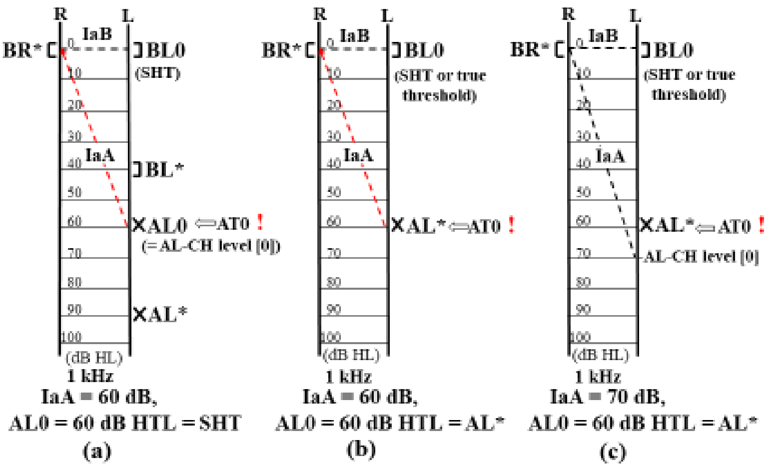


Figure 2-6 IaA ≥ 60 dB

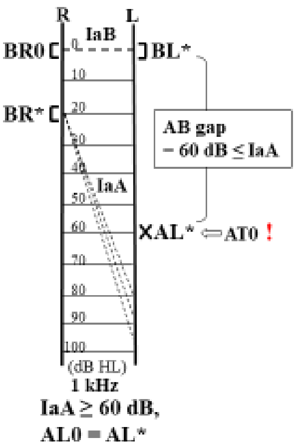


Figure 2-7 BR0 < BR*

(2) An audiogram with adequate masking

Fig. 2-8 shows an audiogram in which adequate masking for AC and BC has been completed at each frequency. The true AC and BC thresholds in the left ear (AL*, BL*) have been obtained, and the apparent AC and BC thresholds in the left ear (AL0s, BL0s) from 500 Hz to 4000 Hz have proved to be SH thresholds. For example, the audiometric configuration at 1000 Hz is as follows:

The SH thresholds: AL0 = 60 dB HTL, BL0 = 5 dB HTL.

The true thresholds: AL* = 90 dB HTL, BL* = 45 dB HTL.

At this point, the apparent BC threshold in the right ear (BR0 of 0 dB HTL) is determined to be the true threshold (BR0 = BR*). The BR* is the first cause of SH for the test signals. (cf. **4.5**).

a) Calculation of the IaA value

The IaA value at 1 kHz can be calculated by

1000 Hz • IaA = AL0 − BR* = 60 (dB HTL) − 0 (dB HTL) = 60 dB.

Therefore, if we can obtain SH thresholds for AC in the left ear (AL0s), the IaA values can be calculated (cf. **1.2-3** **[3]**). However, in cases where the AL0s are true thresholds, such as the AL0 of 40 dB HTL at 250 Hz (AL0 = AL*), the IaA values cannot be determined, and we only know that the IaA value at 250 Hz is larger than or equal to 40 dB:

250 Hz • IaA ≥ AL* − BR0 = 40 (dB HTL) − 0 (dB HTL) = 40 dB.

Furthermore, the IaA values cannot be calculated at frequencies, such as 125 Hz and 8000 Hz, where BC thresholds are not measured. As a result, we only know that:

125 Hz • IaA ≥ AL* − AR* = 40 (dB HTL) − 15 (dB HTL) = 25 dB,

8000 Hz • IaA ≥ AL* − AR* = 75 (dB HTL) − 30 (dB HTL) = 45 dB.

Methods for coping with 125 Hz and 8000 Hz will be discussed in Lecture 5 (cf. **5.6**).

b) Calculation of the IaB value

Since the BL0 at 1 kHz is an SH threshold, the IaB value is calculated as follows:

1 kHz • IaB = BL0 − BR* = 5 (dB HTL) − 0 (dB HTL) = 5 dB.

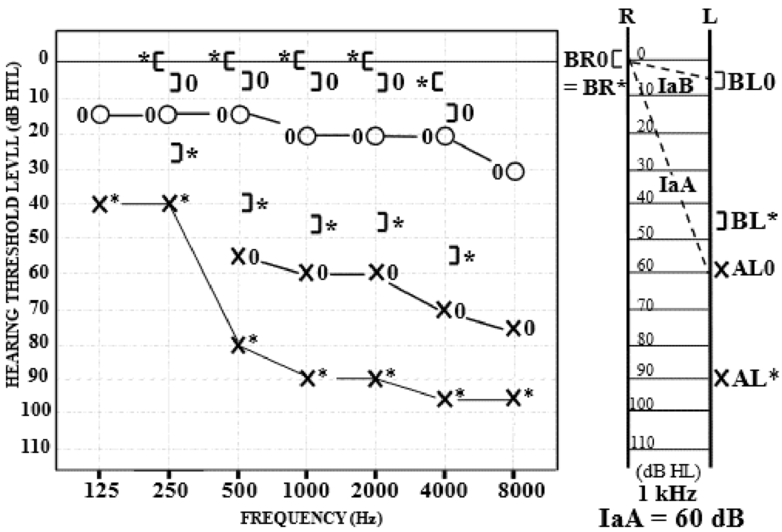


Figure 2-8 Audiogram with adequate masking

c) The first cause of SH

The BC thresholds measured in both ears without masking (BR0, BL0) cannot both be the SH thresholds. In other words, if the BC threshold in one ear is the SH threshold, the other must be the true threshold. When there is a difference between the true BC thresholds of the right and left ears (e.g., BR* < BL*), the true BC threshold in the better ear (i.e., BR*) is the first cause of SH for test signals (cf. **4.5**).

**** Further note ****

*) Since measurement errors of the BC threshold are large, IaB values cannot be obtained with high accuracy. Nevertheless, IaA and IaB should be treated as equivalent because there is no essential difference between AC and BC either in theory or in clinical practice.

) The second cause is that the true AC and BC thresholds in the poorer ear by BC (AL, BL*) are higher than the AL- and BL-CH levels, respectively.

2.2 Masking

2.2-1 Effective masking and ineffective masking

Masking is a phenomenon that occurs when the minimum hearing threshold is elevated due to the presence of noise. In this lecture series, we stipulate that when masking noise is presented to the non-test ear, effective masking refers to elevation in the BC threshold of the non-test ear. If no BC threshold elevation occurs, the masking is ineffective. The masking noise is calibrated in terms of the effective masking level (EML), such that a given masking noise will shift the AC threshold in the non-test ear to a level equal to the masking noise level (ANSI, 2004).

For example, in **Fig. 2-9**, when the true AC threshold in the right (non-test) ear (AR*) is 50 dB HTL, the masking noise of 70 dB HL that is presented to the right ear will shift the AC threshold to 70 dB HTL. This means that the masked AC threshold in the right ear (mAR) is 70 dB HTL. At the same time, the BC threshold in the right ear is also elevated, thus the masking is effective. Furthermore, the AC threshold remains stable with the masking noise of 50 dB HL. Therefore, noises of levels that are higher than the AR* cause effective masking to occur. Here, let the difference between the masking noise level (N) and AR* be "α:"

$$\alpha \text{ (dB)} = N \text{ (dB HL)} - AR^* \text{ (dB HTL)}.$$

Although α has been termed an effective level, in this lecture series, it is termed an effective amount of masking (c.f. **1.3**).

When N ≤ AR* (α ≤ 0 dB), the BC threshold in the non-test ear is not elevated: ineffective masking. When N > AR* (α > 0 dB), the BC threshold in the non-test ear is elevated: effective masking.

Furthermore, let α which corresponds to Nn (the n-th masking noise; n = 1, 2, 3, …) be αn, which can be written as follows:

$$\alpha n \text{ (dB)} = Nn \text{ (dB HL)} - AR^* \text{ (dB HTL)}.$$

Then, the n-th masking noise is as follows:

$$Nn = (AR^* + \alpha n) \text{ dB HL}.$$

The amount of BC threshold elevation of the non-test ear with Nn is termed a masking amount (MAn, n = 1, 2, 3, …). In effective masking, it is presumed that αn (> 0 dB) is equal to the MAn (cf. **2.3-5 [2]**). With a masking noise of Nn in the right ear, the masked and elevated BC threshold in the right (non-test) ear is referred to as the BC threshold of the right ear masked by Nn (mBR[n]), which can be represented as follows:

$$mBR[n] = (BR^* + MAn) = (BR^* + \alpha n) \text{ dB HTL},$$

where MAn = αn (> 0 dB): the masking amount is equal to the effective amount of masking (cf. **2.3-5 [2]**). For example, when N1 = 70 dB HL (α1 = 20 dB),

$$mBR[1] = BR^* + MA1 = BR^* + \alpha 1 = 10 \text{ (dB HTL)} + 20 \text{ (dB)} = 30 \text{ dB HTL}.$$

The AC threshold in the right (non-test) ear is also elevated by the same amount. The AC threshold of the right ear masked by Nn (mAR[n]) is as follows:

$$mAR[n] = (AR^* + \alpha n) \text{ dB HTL} = [Nn] \text{ dB HTL}.$$

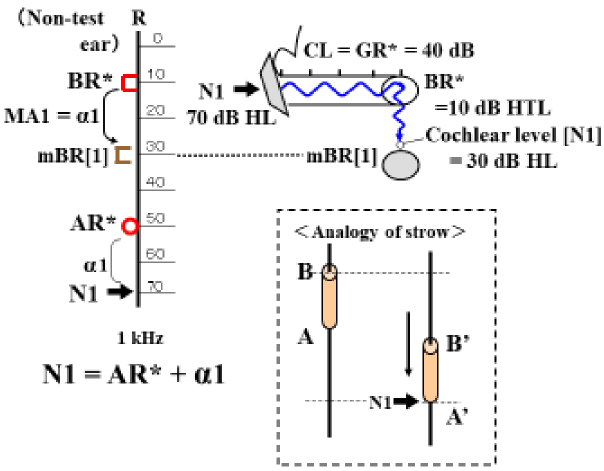


Figure 2-9 Effective masking

< An analogy of a straw >

Let the top edge of the straw be B, and the bottom edge be A. B is BR* and A is AR*. The length of the straw (i.e., AB) is the AB gap of the non-test ear. Now, if the straw is moved downward to the position of the initial masking noise level (N1) along a string, B' is mBR[1], and A' is mAR[1].

**** Further note ****

) "That the BC threshold in the right (non-test) ear is elevated" means that the BC threshold of the non-test ear masked by Nn (mBR[n]) is higher than the true BC threshold in the right ear (BR): mBR[n] > BR*.

2.2-2 A boundary condition

The condition for determining BC thresholds in effective masking must be the same as that in OM, which will be described later. Accordingly, we will first consider universal conditions that determine the BC thresholds in the test and non-test ear with masking.

Let us consider the output levels of signals. In **Fig. 2-10**, when an N1 of 70 dB HL (α1 = 20 dB) is presented to the right (non-test) ear, the mBR[1] is 30 dB HTL (cf. **Fig. 2-9**). Therefore, if a BC test signal, BT1 of 30 dB HL, is presented to the right ear along with the N1, it reaches the right inner ear via the direct BC pathway and is barely heard by that inner ear.

Now, let us discuss this case example with attention to the cochlear levels of signals (**Fig. 2-10**). If the BC test signal delivered to the right (non-test) ear along with N1 is just audible in that inner ear, how many decibels is the cochlear level of the test signal?

The cochlear level of Nn in the AC pathway is termed a masking level [n] (M level [n]). When N1 is 70 dB HL, the M level [1] is as follows (cf. **1.2-1**):

M level [1] = N1 − CL = N1 − GR*
= 70 (dB HL) − 40 (dB)
= 30 dB HL. - - - (1)

At the same time, when the BC test signal is presented to the right ear, and its cochlear level in the right ear is lower than the M level [1], then the signal is not heard. However, the signal is heard when it is higher. Therefore:

a) A BT of 20 dB HL is not heard by the right ear.
Rt cochlear level = 20 dB HL < M level [1].

b) A BT of 40 dB HL is heard by the right ear.
Rt cochlear level = 40 dB HL > M level [1].

c) Especially, when BT1 is 30 dB HL,
Rt cochlear level [BT1] = BT1
= 30 dB HL. - - - (2)

At that point, BT1 is just audible in the right inner ear.

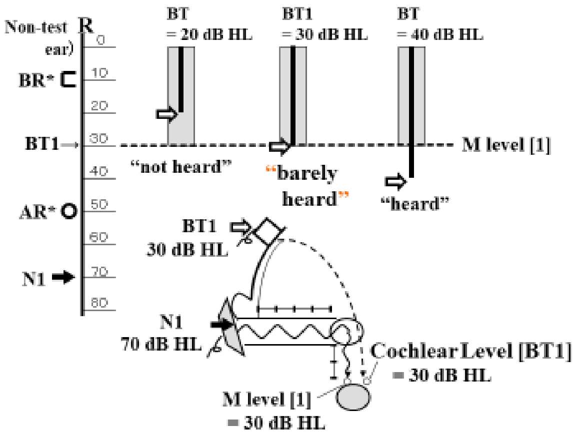


Figure 2-10 Boundary condition

This can be generalized as follows: from equations (1) and (2), the cochlear level [BT1] is equal to the M level [1], which means that the BC test signal (BTn) is barely heard by the non-test inner ear when the cochlear level of the non-test ear [BTn] is equal to the M level [n]. This is a condition that determines the border of the BC threshold in the non-test ear with masking (i.e., "heard" or "not heard") and is called a boundary condition (cf. **Supplement 2**).

The boundary condition for BC thresholds in the non-test ear:
In cases where the M level ≥ BR* (αn ≥ 0 dB), the test signal is barely heard if the cochlear level of the signal is equal to the M level.

This may be referred to as the boundary condition for effective masking.
When the M level = BR* (α = 0 dB, N = AR*), the non-test ear's BC threshold is not elevated.
When the M level > BL* (α > 0 dB, N > AR*), the non-test ear's BC threshold is elevated.
(i.e., mBR[n] = BR* + αn > BR*).

Furthermore, note that the masked BC and AC thresholds are usually calculated theoretically and almost never measured. However, as shown in **Fig. 2-10**, if the BC threshold measured in the non-test ear with N1 (BR1 = 30 dB HTL) can be obtained, it will be equal to the masked BC threshold (BR1 = mBR[1] = 30 dB HTL) (cf. **2.4 [2]**).

**** Further note ****

*) The output level of the masking noise is the masking noise level. In this lecture series, the cochlear level of the masking noise is termed the masking level.

*) When an occlusion effect occurs, the effective amount of masking (α) is not always equal to the masking amount (MA) (cf. **L. 10**).

2.2-3 Effective masking

(1) Masking noise levels and effective amounts of masking (α)

When the masking noise levels are higher than the true AC threshold level in the right (non-test) ear (i.e., Nn > AR*), the non-test ear's BC threshold is elevated by the effective amounts of masking (αn = Nn − AR* > 0 dB). As shown in **Fig. 2-11**, Even if noises of the same level are presented to the non-test ear, the larger the effective amounts of masking, and the higher the BC threshold levels in the non-test ear become. Hence, the non-test ear's BC threshold masked by Nn (mBR[n]) may be reduced to the following formula:

mBR[n] = BR* + αn
= BR* + (Nn − AR*)
= Nn − (AR* − BR*)
= Nn − GR*.

∴ mBR[n] = Nn − GR*,

where GR* is the true AB gap of the right ear (i.e., GR* = AR* − BR*).

Therefore, the masked BC threshold is expressed in two forms as follows:

mBR[n] = BR* + αn
= Nn − GR*
(= M level [n]).

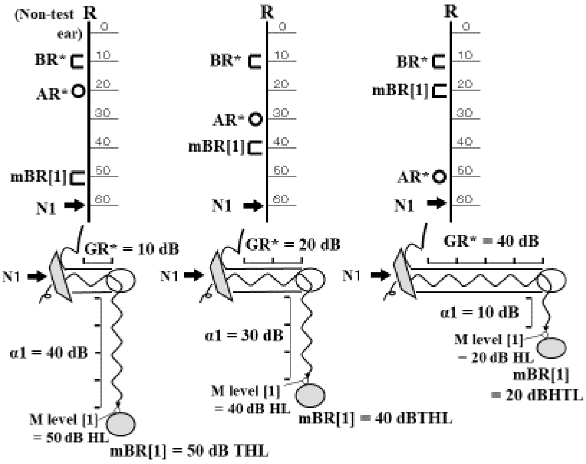


Figure 2-11 Right ear's BC threshold masked by Nn

The other side of the coin is that even if noises of the same levels are presented to the non-test ear, the larger the true AB gaps of the non-test ear, and the lower the BC threshold levels in that ear become. Consequently, the masking effect decreases. The true AB gap of the non-test ear is a factor that determines the difficulty level of masking (cf. **5.7**).

(2) Effective masking via the direct-converted BC pathway

When the air-conductive disorders are particularly severe in one ear (such as in the case of the right ear in **Fig. 2-12**), the AC masking noise cannot travel to the right inner ear via the AC pathway. Instead, the masking effect is provided by the converted BC noise that reaches the inner ear via the direct-converted BC pathway. At this time, the true AB gap of the right (non-test) ear is equal to IaA (GR* = IaA) (cf. **1.4**, **5.7**). The cochlear level of N1 in the direct-converted BC pathway, which is also termed the M level [1], can be represented as follows:

M level [1] = N1 − IaA
= N1 − GR*.

A typical case of such a severe disorder is atresia of the external canal. Others might be ossicular discontinuity and otosclerosis. As a result, the M level is described as the same equation via the AC or direct-converted BC pathway:

M level [n] = Nn − GR*.

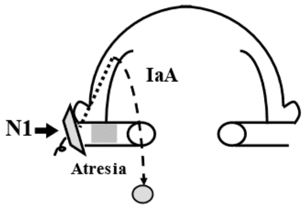


Figure 2-12 Masking via the direct BC pathway

(3) The inner ear with mBR[n] of Z dB HTL

When masking in the right ear with Nn, let the BC threshold of the right ear masked by Nn (mBR[n]) be Z dB HTL for any given value of Z (**Fig. 2-13**). Depending on the boundary condition for effective masking, when the AC and BC test signals are presented, they are barely heard by mBR[n] as far as their cochlear levels are equal to Z dB HL, regardless of the transmission pathways.

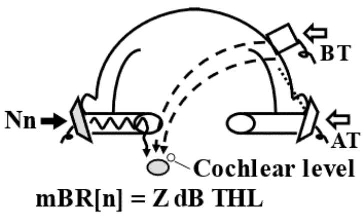


Figure 2-13 mBR[n] = Z dB THL

**** Further note ****

*) When effective masking occurs via the direct BC pathway, masking for BC becomes impossible, because both the M and OM levels are equal regardless of the type of earphones.

2.2-4 The masked BC threshold and CH level

When N1 is introduced to the right (non-test) ear:

N1 = (AR* + α1) dB HL, (α1 > 0 dB),

The masking amount of N1 is equal to α1 (MA1 = α1). Thus, the BC threshold in the right ear is elevated by α1 from BR*:

mBR[1] = (BR* + α1) dB HTL.

Concomitantly, the CH levels in the left (test) ear are also elevated by α1.

BL-CH level [1] = mBR[1] + IaB = (BR* + α1) + IaB
= (BR* + IaB) + α1
= BL-CH level [0] + α1.

AL-CH level [1] = mBR[1] + IaA= (BR* + α1) + IaA
= (BR* + IaA) + α1
= AL-CH level [0] + α1.

The configuration in **Fig. 2-14 (a)** shows that the AL* is 75 dB HTL and the BL* is 35 dB HTL. When an AC test signal (AT0 of 60 dB HL) is presented to the left ear without masking, it is barely heard by the right inner ear (BR* = 0 dB HTL) and is not received by the left inner ear (BL*). Therefore, the AL0 is 60 dB HTL, likewise the SH threshold.

Next, in **Fig. 2-14 (b)**, we can see that when the initial masking noise (N1 = 50 dB HL, α1 = 20 dB) is directed to the right ear, the BC threshold of the right ear masked by N1 (mBR[1]) is 20 dB HTL. Then, the AL-CH level is elevated by 20 dB (= α1):

AL-CH level [1] = AL-CH level [0] + α1 = 60 (dB HL) + 20 (dB)
= 80 dB HL.

At this time, the AT0 of 60 dB HL is no longer heard. Subsequently, the AC test signal levels are increased by 5-dB steps. When the AT1 is 75 dB HL,

Rt cochlear level [AT1] = AT1 − IaA = 75 (dB HL) − 60 (dB)
= 15 dB HL (< mBR[1] = 20 dB HTL). - - - not heard

Lt cochlear level [AT1] = AT1 − GL* = 75 (dB HL) − 40 (dB)
= 35 dB HL (= BL* = 35 dB HTL). - - - heard

Since the AT1 is barely heard by the test inner ear (BL*) and not received by the non-test inner ear (mBR[1]), the hearing of the AT1 is true. The AC threshold measured in the left ear with N1 (AL1) of 70 dB HTL is the true AC threshold.

For BC, the apparent BC threshold in the left ear (BL0) of 5 dB HTL is the SH threshold (**Fig. 2-14 [a]**). The BC threshold measured in the left ear with N1 (BL1) of 25 dB HTL is also the SH threshold (**Fig. 2-14 [b]**).

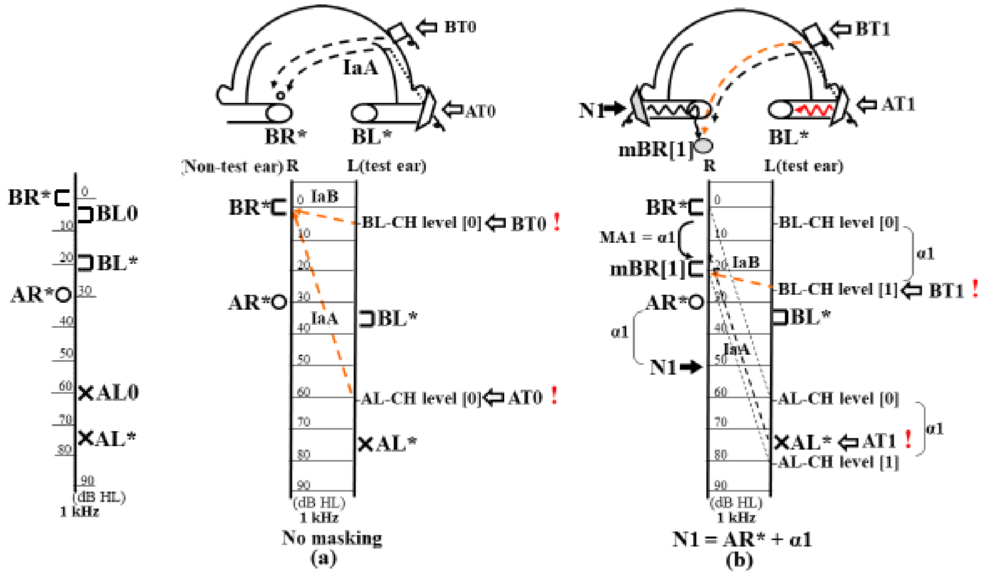


Figure 2-14 CH levels in effective masking

**** Further note ****

*) AT1 is the AC test signal that the participant barely hears when masking with N1, likewise for BT1 as regards the BC test signal.

*) It can be said that since AT1 is lower than the AL-CH level [1], it is not heard by the right cochlea.

2.3 Overmasking

2.3-1 Effective masking and overmasking

When the AC masking noises (Nn, n = 1, 2, 3, . . .) are introduced to the right (non-test) ear using supra-aural earphones, they reach the left (test) inner ear as converted BC noises via the cross-converted BC pathway (**Fig. 2-15**). At this time, OM refers to elevation in the BC threshold of the test ear. In terms of BC threshold elevation, effective masking (i.e., the BC threshold elevation in the non-test ear) and OM (i.e., the BC threshold elevation in the test ear) are the same event or masking phenomenon (cf. **1.1-2** **[2]**). Therefore, the discussions related to effective masking are true in the same way as those related to OM (**Table 2-1**).

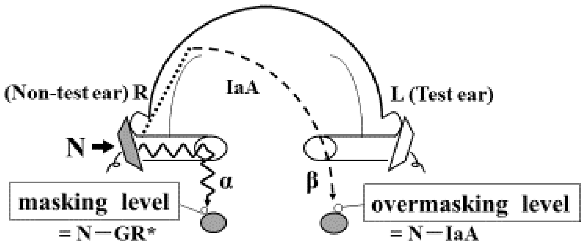


Figure 2-15 Effective masking and overmasking

Table 2-1 Effective masking and overmasking

	Effective masking The BC threshold elevation in the right, non-test ear	**Overmasking** The BC threshold elevation in the left, test ear
Requirements	M level [n] > BR*	OM level [n] > BL*
Amounts of the threshold elevation	MAn	OMAn
Elevated BC thresholds	mBR[n] = BR* + MAn = BR* + αn = M level [n] = Nn − GR*	omBL[n] = BL* + OMAn = BL* + βn = OM level [n] = Nn − IaA
Effective amounts	αn = M level − BR* = Nn − AR*	βn = OM level − BL*

2.3-2 An OM level

The cochlear level of the masking noise (Nn) in the cross-converted BC pathway is referred to as an OM level [n]:

OM level [n] = (Nn − IaA) dB HL, (n = 1, 2, 3, …).

Let the difference between the OM level [n] and BL* be "βn:"

βn (dB) = OM level[n] (dB HL) − BL* (dB HTL).

On the model of α (the effective amount of masking), β is termed an effective amount of OM. The requirement for the test ear's BC threshold to be determined is as follows:

> **The boundary condition for BC thresholds in the test ear:**
> In cases where the OM level ≥ BL* (βn ≥ 0 dB), the test signal is barely heard if the cochlear level of the signal is equal to the OM level.

This may be referred to as the boundary condition for OM.
When the OM level = BR* (β = 0 dB), the test ear's BC threshold is not elevated.
When the OM level > BL* (β > 0 dB), the test ear's BC threshold is elevated.

In OM, it is assumed that βn (> 0 dB, n = 1, 2, 3, …) is equal to the amount of threshold elevation in the test ear with Nn, which is termed an OM amount (OMAn). The masked and elevated BC threshold in the left (test) ear, which is referred to as the BC threshold of the left ear overmasked by Nn (omBL[n]), is represented as follows:

omBL[n] = (BL* + OMAn)
= (BL* + βn) dB HTL,

where OMAn = βn (> 0 dB): the OMAn is equal to the effective amount of OM.

2.3-3 An example of overmasking

Now, let us consider OM in a case in which the BL* is 20 dB HTL.

(1) When the initial masking noise level, N1 = 60 dB HL (**Fig. 2-16**),

OM level [1] = N1 − IaA = 60 (dB HL) − 60 (dB)
= 0 dB HL (< BL* = 20 dB HTL).

Since the OM level [1] is lower than BL* (β1 = −20 dB), N1 is not heard by the left inner ear and the BC threshold in the test ear is not elevated. Therefore, N1 does not cause OM.

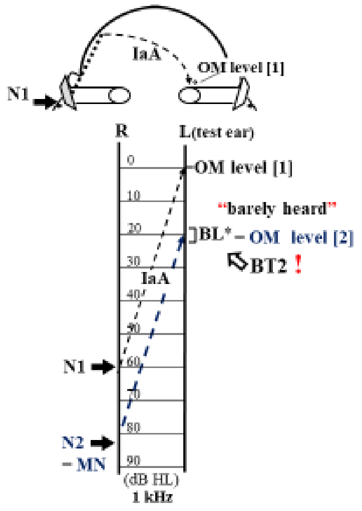


Figure 2-16 OM levels

(2) When the second masking noise level, N2 = 80 dB HL (**Fig. 2-16**),

OM level [2] = N2 − IaA = 80 (dB HL) − 60 (dB)
= 20 dB HL (= BL* = 20 dB HTL).

Since the OM level [2] is equal to BL* (β2 = 0 dB), N2 is barely heard by the left inner ear (i.e., CH of the noise). Here, when a BT2 of 20 dB HL is presented to the left ear,

Lt cochlear level [BT2] = 20 dB HL = OM level [2].

Depending on the boundary condition for OM, the BT2 is just audible in the left inner ear. The BC threshold measured in the left ear with N2 (BL2) is 20 dB HTL (i.e., BL2 = BL*). Thus, N2 does not cause OM.

Here, OM occurs when the noise levels are higher than 80 dB HL (= N2). Therefore, the maximum level of masking noise at which OM does not occur (MN) is given by

MN = (BL* + IaA) dB HL.

Note that MN cannot be determined until BL* and IaA have been obtained.

(3) When the third masking noise level, N3 = 90 dB HL (**Fig. 2-17**),

OM level [3] = N3 − IaA = 90 dB HL − 60 dB
= 30 dB HL (> BL* = 20 dB HTL).

Since the OM level [3] is higher than BL* (β3 = 10 dB), N3 is perceived by the left inner ear. As a result, the BT2 of 20 dB HL is no longer audible. Therefore, the BC threshold in the test ear is elevated, i.e., N3 causes OM. Depending on the boundary condition for OM, the BC threshold level of the left ear overmasked by N3 (omBL[3]) is equal to the OM level [3]:

omBL[3] = 30 dB HTL (= OM level [3]).

Otherwise, since β3 = OM level [3] − BL* = 10 dB,

omBL[3] = BL* + β3 = 20 (dB HTL) + 10 (dB)
= 30 dB HTL.

In the left ear, with the BC threshold elevation, the AC threshold is also elevated. The AC threshold of the left ear overmasked by N3 (omAL[3]) is as follows:

omAL[3] = AL* + β3 = 70 (dB HTL) + 10 (dB)
= 80 dB HTL.

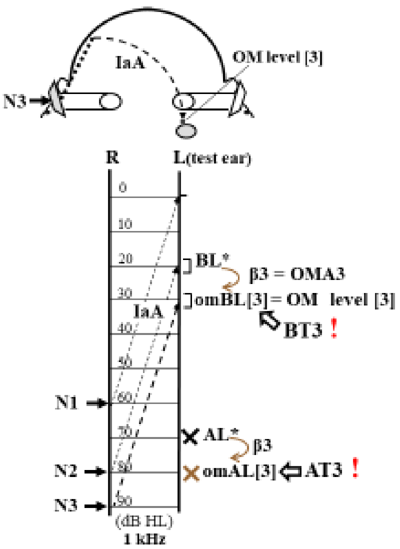


Figure 2-17 Overmasking

The overmasked BC and AC thresholds are theoretically calculated thresholds (cf. **2.4 [2]**). Clinically, they are obtained as the thresholds measured in the test ear. When an AT3 of 80 dB HL and a BT3 of 30 dB HL are delivered to the left (test) ear, they are barely heard by the test inner ear (omBL[3]). The AC threshold measured in the left ear with N3 (AL3) is 80 dB HTL and the BC threshold measured in the left ear with N3 (BL3) is 30 dB HTL. Both AL3 and BL3 are equal to the overmasked thresholds (AL3 = omAL[3], BL3 = omBL[3]).

**** Further note ****

) "That the BC threshold in the left (test) ear is elevated" means that the BC threshold measured in the test ear with Nn (BLn) is higher than the true BC threshold in the left ear (BL): BLn > BL*.

2.3-4 Significance of β (= 0 dB)

The boundary condition for OM shows

1) The BC threshold in the test ear is not elevated when the OM level = BL* (β = 0 dB),
2) The BC threshold in the test ear is elevated when the OM level > BL* (β > 0 dB).

The reason is derived from the EML prescription that the BC threshold in the non-test ear is not elevated when α = 0 dB (cf. **2.2-1**).

As shown in **Fig. 2-18 (a)**, in the audiometric configuration (GR* = 50 dB, GL* = 50 dB, IaA = 60 dB), when the initial masking noise level is equal to the true AC threshold level in the non-test ear (i.e., N1 = 60 dB HL = [AR*], α1 = 0 dB), the M level [1] is equal to the true BC threshold level in the non-test ear (M level [1] = 10 dB HL = [BR*]). Thus, the BC threshold in the non-test ear is not elevated. Conversely, since the OM level [1] is equal to the true BC threshold level in the test ear (OM level [1] = 0 dB HL= [BL*]), the BC threshold in the test ear is not elevated: N1 is the maximum level of masking noise at which OM does not occur (MN).

Next, as shown in **Fig. 2-18 (b)**, when N2 = 75 dB HL (α2 = 15 dB), the BC threshold in the non-test ear is elevated by 15 dB (= α2) (mBR[2] = 25 dB HTL) and the BC threshold in the test ear is also elevated by 15 dB (= β2) (omBL[2] = 15 dB HTL). As a result, the AC threshold in the test ear is elevated by the same amount (β2).

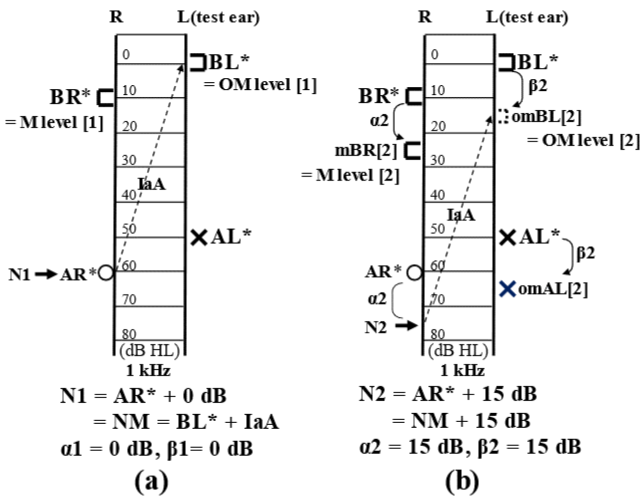


Figure 2-18 Boundary condition for overmasking

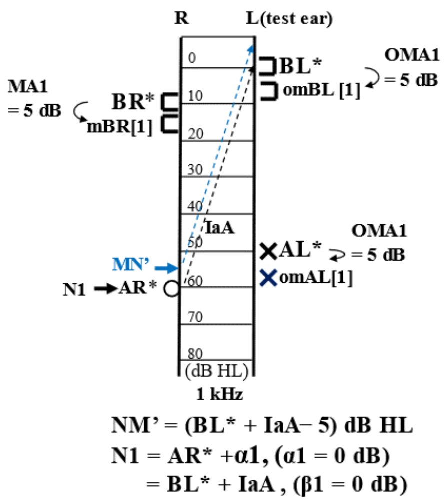


Figure 2-19 MN' = BL* + IaA – 5

However, some authorities have stated that the maximum level of masking noises at which OM does not occur can be calculated as shown below (Lloyd & Kaplan, 1978):

MN' = (BL* + IaA – 5) dB HL.

If this equation is correct, as in **Fig. 2-19**, OM occurs when N1 of 60 dB HL (= BL* + IaA, α1 = 0 dB) is introduced into the right ear, which means that the test ear's BC threshold is elevated when β1 = 0 dB. Inevitably, when α1 = 0 dB (i.e., N1 = 60 dB HL = [AR*]), the non-test ear's BC threshold will be elevated. This goes against the EML prescription (cf. **2.2-1**). To maintain logical consistency, the condition of determining the threshold in effective masking must be the same as that used in OM because the same masking phenomenon is involved. This is why the boundary conditions are required (cf. **supplement 2**).

In theory, boundary conditions based on the American National Standards Institute (ANSI) 2004 are agreements. However, in actuality, those conditions do not always hold true. Such cases will be discussed in Lecture 8.

**** Further note ****

*) Gelfand (2009) discussed the MN in an exact way.

*) The commitments: when the cochlear levels of both noises and test signals are higher than or equal to the BC threshold level of that cochlea, the test signals are barely heard with a one-in-two probability. Then, we commit to the proposition that they are always barely heard.

*) Clinically, the difference of only 5 dB in threshold is a measurement error and within the acceptable range. However, theoretically, MN and MN' do not go together.

2.3-5 An inner ear with a BC threshold of Z dB HTL

(1) The transmission pathways and cochlear levels

Signals (AC and BC test signals, AC masking noises, and converted BC signals) are attenuated by a certain amount in transmission pathways before they reach the inner ear (**Fig. 2-20**). Whether or not those signals are heard is determined by the connection between the cochlear levels of the signals and the BC threshold level in the inner ear, regardless of the transmission pathway.

In an inner ear with a BC threshold of Z dB HTL, the signals can be barely heard by the cochlea as far as the cochlear levels in that inner ear are Z dB HL. Here, the BC threshold may be the true BC threshold (BR*), the masked BC threshold (mBR[n]) or the overmasked BC threshold, (mBL[n]) (**Fig. 2-20 [b]**) (cf. **Fig.1-27**, **Fig. 2-13**).

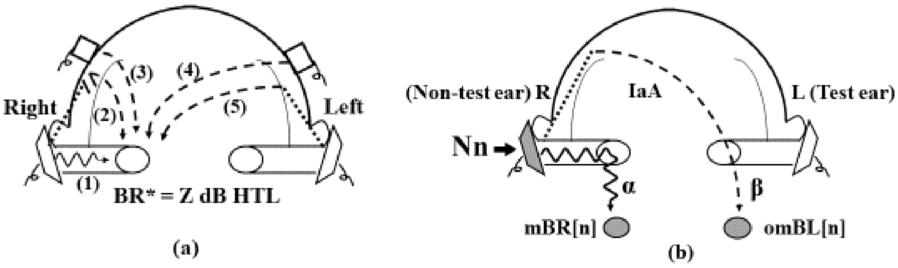


Figure 2-20 Inner ear with the BC threshold of Z dB HTL

(2) The effective amount of masking (α) and masking amount (MA)

In this lecture series, the difference between the masking noise level and the true AC threshold level in the non-test ear has been termed the effective amount of masking (α = N − AR*) (cf. **2.2-1**). The one-for-one elevation of the noise levels and the BC thresholds levels in the non-test ear occurs when α ≥ 10 dB. At this time, α is equal to the amount of the BC threshold elevation in the non-test ear (the masking amount: MA): α = MA.

Here, as shown in **Fig. 2-21 (a)**, let us assume that the amount of BC threshold elevation in the participant's non-test ear is 3 dB (i.e., MA1 = 3 dB) when α1 = 5 dB (N1 = 25 dB HL). If the BC thresholds can be measured via 1-dB steps, the BC threshold measured in the test ear with N1 (BL1) is 13 dB HTL, which means an α1 of 5 dB is not equal to an MA1 of 3 dB (α1 ≠ MA1). However, in fact, since the test signal's output is a 5-dB step in pure tone audiometry (PTA), a BT1 of 15 dB HL presented to the test ear is just audible, i.e., the BL1 is 15 dB HTL (**Fig. 2-21 [b]**). Therefore, when α1 = 5 dB, the amount of the non-test ear's BC threshold elevation in PTA may be assumed to be 5 dB.

The same holds true for the effective amount of OM (β). Therefore, to simplify the discussion, it is assumed that when α ≥ 0 dB and β ≥ 0 dB, α and β are equal to the amount of the BC threshold elevations in the non-test and test ear, respectively.

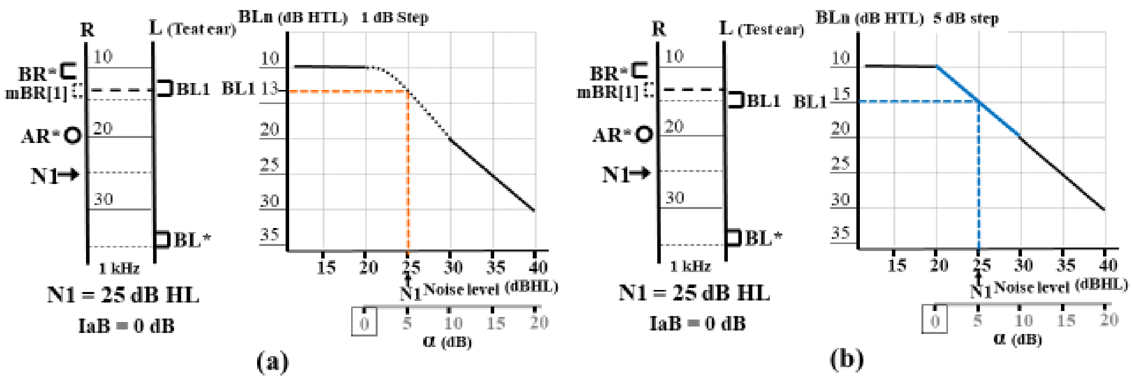


Figure 2-21 Effective amount of masking (α) and masking amount (MA)

**** Further note ****

) When the occlusion effect (OE) occurs in the non-test ear, the masking effect is decreased by the OE value. Then, the effective amount of masking (α = N − AR) is not equal to the masking amount with the OE (oe-MA = α − OE). Therefore, we must define them separately (cf. **L. 10**).

*) When α ≥ 0 dB, α (an effective amount of masking) is equal to a masking amount (MA).
When β ≥ 0 dB, β (an effective amount of overmasking) is equal to an overmasking amount (OMA).

2.4 Points of attention

(1) The numerical value of a physical quantity

a) Interaural attenuation is a physical quantity. The numerical value gained by measuring the physical quantity is a value. For example, the numerical value obtained by measuring IaA is the IaA value. Although the physical quantity and its value should be considered separately in a rigorous sense, the IaA value is sometimes described as IaA in this lecture series.

b) In the operation of levels and quantities (amounts), each term of equality and inequality is represented as a numerical value. For instance, when N = 70 dB HL and the IaA value = 60 dB,

OM level = N − IaA = 70 (dB HL) − 60 (dB) = (70 − 60) dB HL
= 10 dB HL.

The IaA value is determined by the following formula:

IaA = AL0 − BR0 = 65 (dB HTL) − 5 (dB HTL)
= 60 dB,

where AL0 = 65 dB HTL (the SH threshold), BR0 = 5 dB HTL (= BR*).

Furthermore, "The noise level of 50 dB HL is higher than the right ear's true AC threshold level, (AR* = 40 dB HTL)," which may be written as

N > AR*: 50 (dB HL) > 40 (dB HTL).

In particular, "the masking noise is set to a level equal to the right ear's true AC threshold level (AR* = 40 dB HTL)," which is described as follows:

N = [AR*] dB HL
= 40 dB HL,

where the square bracket represents the numerical value of AR*, 40.

(2) Levels that are measured and those that are not

The right and left ear's AC and BC threshold levels are the results of actual measurements. However, some of the levels defined in Lecture 2 are mentally calculated by the examiner. These should be identified.

a) The non-test ear's BC threshold masked by Nn: mBR[n] = BR* + αn.

The examiner calculates the mBR[n] using the above formula. Usually, this threshold level is not measured.

b) The test ear's BC thresholds overmasked by Nn: omBL[n] = OM level [n] = BL* +βn.

When OM occurs, the examiner calculates the omBL[n] using the above formula. At this time, the level is not measured. Subsequently, the BC thresholds in the test ear are measured. The BC test signal (BTn) of a level equal to the omBL[n] is barely heard by the participant, and the test ear's BC threshold measured with Nn (BLn) is equal to the omBL[n]. Therefore, the omBL[n] turns out to be the measured level in the end (cf. **2.3-3 [3]**). The same goes for omAL[n].

c) CH level: AL-CH level [0] = BR0 + IaA.

Without masking, the examiner predicts the AL-CH level [0] using the above formula. Here, since the IaA value is not known, the CH level itself is not determined. When the left ear's AC threshold level measured without masking (AL0) is evidently lower than the predicted AL-CH level [0], the examiner can determine the AL0 as the true threshold. At this time the CH level is not measured. Conversely, if the AL0 proves to be the SH threshold with adequate masking noise in the non-test ear, the IaA value (AL0 − BR0) is determined and the AL-CH level [0] is established. The shadow curve of the AL0s represents the AL-CH levels [0] that have been measured. The same goes for BC.

The same holds true for quantities or amounts. For example, the IaA value can be measured only when the apparent AC threshold has proved to be the SH threshold as previously described.

**** Further note ****

*) the operation of levels and quantities is that of numerical values, and is referred to as the numerical value equation.

(3) The non-test ear and the test ear

In principle, it is assumed that the right ear is the non-test ear and the left ear is the test ear.

Non-test (right) ear	Test (left) ear
The ear to which the noise is presented	The ear to which the test signal is presented
The ear masked by the noise, Nn (The masked ear)	The ear measured using test signals
The BC threshold masked by Nn (mBR[n])	The AC and BC thresholds measured with Nn (ALn, BLn)

The non-test ear: In effective masking, BC threshold in the non-test ear is elevated. The elevated threshold is the BC threshold of the non-test ear masked by Nn (mBR[n]).

The test ear: The AC and BC thresholds measured in the test ear with Nn (ALn, BLn) are obtained when the AC and BC test signals are barely heard.
In undermasking, the measured AC and BC thresholds are the SH thresholds.
In adequate masking, they are the true hearing thresholds.
In OM, they are the overmasked hearing thresholds.
There are four types of hearing of test signals: true hearing, CH, SH and overmasked hearing.

(4) The term "masking"

Since "masking" has multiple meanings and cannot be defined unambiguously, it is necessary to clarify what we mean when we use the term.

a) "To mask the non-test ear" means the following:

1) Simply, "to present a noise to the non-test ear." In other words, it does not matter whether or not the BC threshold in the non-test ear is elevated (i.e., effective, or ineffective masking).
2) "To cause the elevation of the non-test ear's BC threshold." It is a separate matter if the threshold elevation is sufficient to eliminate SH (i.e., avoiding undermasking).
3) "A series of processes intended to obtain the true threshold in the test ear using masking noises at levels that will cause neither SH nor OM (i.e., adequate masking noises)." True thresholds cannot always be obtained. The title of this lecture series is used for this definition.

b) The expression "masking" refers to the following:

In general, "masking is needed" means that we need to input masking noise to the non-test ear and attempt to obtain the true threshold in the test ear. In this lecture series, "masking the right ear in order to obtain the left ear's true AC threshold" is simply referred to as "masking for the left AC." It should be noted that the ear to which the noise is introduced is the right ear.

"Masking for the left AC is needed" means that the masking noise needs to be presented to the right ear in order to obtain the left ear's true AC threshold.

"Masking for the left AC is easy (to perform)" means that when the masking noise is presented to the right ear, the left ear's true AC threshold can be determined with ease.

(5) Cross over, CH, and SH

Cross over: the sounds reach the opposite cochlea via the cross BC pathway. It does not matter whether they are heard by the cochlea or not.

CH: the signals (i.e., test signals or masking noises) reach the opposite cochlea via the cross BC pathway and are heard by the cochlea. It does not matter whether or not they are heard by the cochlea to which they are presented.

SH: the test signals reach the opposite cochlea via the cross BC pathway and are heard by the cochlea. The signals are not heard by the cochlea to which they are presented.

**** Further note ****

*) Conventionally, the masked threshold refers to the test ear's threshold measured with masking. In this lecture series, the term "masked" is used only in the non-test ear (masked ear) and not used in the test ear. It is the non-test ear's BC threshold that is masked by noises.

2.5 Summary of Lecture 2

1. Cross hearing (CH) is defined as hearing the sounds (test signals or masking noises) presented to one ear by the opposite ear, regardless of whether or not they are heard by the ear to which they are presented. Shadow hearing (SH) is defined as hearing the test signals by the non-test inner ear, and not by the test inner ear.

2. The minimum hearing level (dB HL) at which CH of the test signals occurs is referred to as the cross-hearing level (CH level). Without masking, the CH levels for AC and BC in the left ear that correspond to the true BC threshold in the right ear (BR*) are given by

AL-CH level [0] = BR* + IaA,

BL-CH level [0] = BR* + IaB.

The CH level provides an indicator used to determine whether the measured thresholds might possibly be SH thresholds or not. Additionally, in the operation of levels and quantities (amounts), each term of equality and inequality is represented as a numerical value.

3. At some frequency, if the SH thresholds for AC and BC in the left ear (AL0, BR0) are obtained, the IaA and IaB value at that frequency can be calculated by

IaA = AL0 − BR*,

IaB = BL0 − BR*,

where BR* is the true BC threshold in the right ear, and is the first cause for SH.

4. When the masking noise calibrated in terms of the effective masking level (EML) is presented to the non-test ear (e.g., the right ear), noises of the level lower than or equal to the true AC threshold level in the non-test ear (N ≤ [AR*]) cause ineffective masking; i.e., the non-test ear's BC threshold is not elevated. Noises of the level higher than AR* (N > [AR*]) cause effective masking; i.e., the non-test ear's BC threshold is elevated.

5. The n-th masking noise (n = 1, 2, 3, …, αn > 0 dB) causes effective masking:

Nn = (AR* + αn) dB HL, (n = 1, 2, 3…, αn > 0 dB),

where αn is the effective amount of masking of Nn and is equal to the masking amount (α = MA).

The BC threshold of the right (non-test) ear masked by Nn (mBR[n]) is represented as follows:

mBR[n] = (BR* + αn) dB HTL, (αn > 0 dB).

The cochlear level of Nn in the AC pathway is termed a masking level [n] (M level [n]):

M level [n] = Nn – CL = Nn − GR*

6. The boundary conditions

a) The boundary condition for BC thresholds in the right, non-test ear (effective masking)

In cases where the M level ≥ BR* (the true BC threshold in the non-test ear) (αn ≥ 0 dB), the test signal is barely heard if the cochlear level of the signal is equal to the M level.

b) The boundary condition for BC thresholds in the left, test ear (overmasking)

In cases where the OM level ≥ BL* (the true BC threshold in the test ear) (βn ≥ 0 dB), the test signal is barely heard if the cochlear level of the signal is equal to the OM level,

where βn is the effective amount of overmasking of Nn.

7. The maximum level of masking noise at which OM does not occur (MN) is given by

MN = (BL* + IaA) dB HL,

where BL* is the true BC threshold in the test ear. MN cannot be determined until BL* and IaA have been obtained. When OM occurs, the BC threshold of the left (test) ear overmasked by Nn (omBL[n]) is represented as follows:

omBL[n] = (BL* + βn) dB HTL, (βn > 0 dB).

8. In an inner ear with a BC threshold of Z dB HTL, the signals (test signals, masking noises, or converted BC signals) can be barely heard by the cochlea so fa as the cochlear levels in that inner ear are Z dB HL regardless of the transmission pathway. The BC threshold may be the true BC threshold (BR*), the masked BC threshold (mBR[n]), or the overmasked BC threshold, (mBL[n]).