OPEN ACCESS GUIDE TO AUDIOLOGY AND HEARING AIDS FOR OTOLARYNGOLOGISTS

PURE TONE AUDIOMETRY

Maggi Soer

Pure tone audiometry is generally the 1st quantitative hearing test done to assess the nature and degree of hearing loss in adults and in children over about four years of age to properly plan the most appropriate interventions. Other tests include immittance testing (testing middle ear function) and speech audiometry.

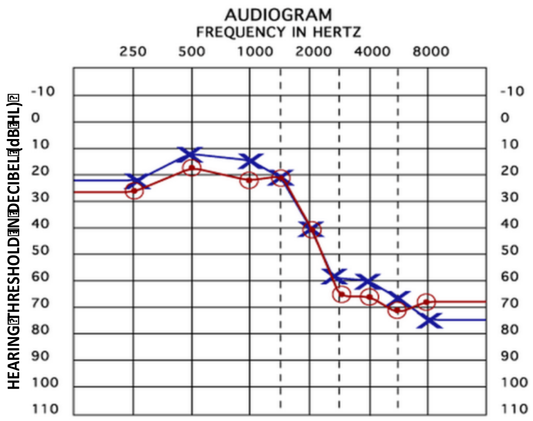
Introduction to pure tone audiometry

Pure tone air conduction and bone conduction tests determine whether or not there is any hearing loss; what type of hearing loss it is; the frequencies that are affected (configuration); and whether hearing loss is unilateral or bilateral. Even though pure tone audiometry is a useful measure of basic hearing function, it does not indicate how well speech is received or understood.

Pure tone audiometry indicates what ***hearing thresholds (dB)*** are required to just be able to perceive a tone at different ***frequencies (Hz)***. A pure tone audiology threshold at a specific frequency is the decibel level at which a sound is perceived 50% of the time. The decibel scale used in pure tone audiometry is ***dB Hearing Level (dB HL)***. The dB HL intensity scale is based on normal human hearing with 0 dB HL representing the median threshold for otologically normal young adults.

Pure tone testing is the measurement of an individual's hearing sensitivity to calibrate pure tones at different frequencies. The basic audiological assessment focuses on pure tone air conduction thresholds in the frequency range 0.25 - 8 KHz. The test is conducted in a sound isolated environment. Each ear is tested separately using various transducers such as headphones, insert earphones or bone conductors. As it is a behavioural test, it is dependent on the response from the individual being tested.

Pure tone thresholds at each frequency are plotted on a graph called an *audiogram*, which depicts the type, degree and configuration of the hearing loss *(Figure 1)*.



	Unmasked Air	Unmasked Bone	Unmasked Air	Masked Bone
R	O	<	△	⊏
L	X	>	□	⊐

No Response	Sound Field
↓	S

Figure 1: Example of pure tone audiogram and symbols recommended by the American Speech-Language-Hearing Association (ASLHA)

Introduction to audiometers

Pure tone audiometers are used to measure hearing thresholds *(Figure 2)*. They vary from simple, inexpensive screening devices used in public health programs, to more elaborate and expensive diagnostic audiometers used in hospitals and clinics. They yield quantitative as well as qualitative information about hearing sensitivity.

Certain components are common to all audiometers:

- ***Audio oscillator*** generates pure tones of different frequencies, usually at discrete steps of 125, 250, 500, 750, 1000, 2000, 3000, 4000, 6000 and 8000 Hz

Figure 2: Pure tone audiometer

- ***Amplifier*** amplifies the produced oscillations to a fixed intensity level (*e.g.* 110 dB HL) without appreciable distortion
- ***Attenuator*** controls the amplified oscillations so that the energy reaching the ear may be varied over a range of 0 to 110 dB HL in 5 dB HL increments. The maximum intensity allowed at each frequency is indicated on the hearing level disc. Due to variations in sensitivity of the ear at different frequencies, more energy is needed at the very low and very high frequencies. For this reason, only the midfrequencies (1000 Hz to 3000Hz) may be presented at a level of 110 dB HL. For all the other frequencies a reduced maximum value is indicated. Due to lower sensitivity for bone conduction, these maximum values are lower for bone conduction than for air con-duction. The maximum hearing level for the lower frequencies (125 – 250 Hz) is generally 70 dB HL
- ***Earphones*** transform electrical energy into acoustic energy which is presented to the ear. Alternatively a ***bone conductor*** may be used when the sound is to be sent directly to the inner ear via the skull. ***Rubber cushions*** are fitted to the earphones. Alternatively ***insert earphones*** may be used, which are inserted into the ears *(Figures 3, 4)*

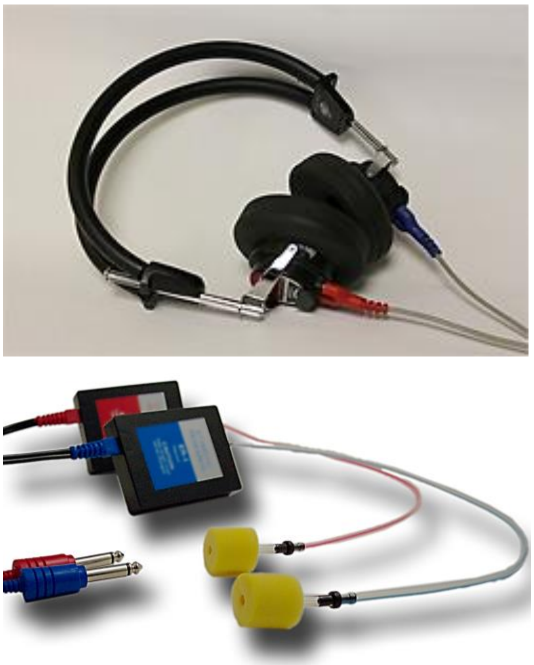


Figure 3: Transducers: Supra-aural & insert earphones

- Producing a ***masking noise*** is an important facility available on most audiometers. Masking is especially required when the hearing thresholds differ significantly between of the ears.

It is necessary to ***calibrate the audiometer*** to ensure accurate testing. Exchange of information across the world is possible if audiometers are all calibrated in the same way. The *Calibration Standard of the International Standards Organisation (ISO)* has been widely accepted; some countries, including the USA, have their own standards *(ANSI).* According to this standard the audiometer is adjusted in such a way that a previously determined sound pressure for each frequency is delivered to the earphone. This known sound pressure was determined by testing large numbers of 18-25yr olds with normal hearing to determine how much sound pressure must be delivered to the earphone to reach normal hearing thresholds.

Pure tone audiometry

An ***audiogram*** *(Figure 1)* is a graphic representation of a hearing test. With a pure tone test, it is called a ***pure tone audiogram***. It is usually drawn in graphic form, with the frequencies of the signals presented on the horizontal axis (Hertz / Hz) and the intensities of the signals on the vertical axis (decibels / dB).

Pure tone audiometry determines a ***hearing threshold i.e. the lowest level in dB HL at which certain sounds can just be heard 50% of the time that it is presented at that level.*** This threshold is then plotted on the audiogram and the value is compared to normal and abnormal thresholds. *Figure 1* is an example of such an audiogram and the associated symbol system recommended by the *American Speech-Language-Hearing Association (ASLHA).* Consult the open access chapter on audiogram interpretation for additional information.

Pure Tone Air Conduction Testing

Pure tone air conduction audiometry determines the hearing levels at different frequencies at which one can only just hear a tone presented to the external ear canal. ***Before testing is commenced, very clear instructions must be given*** so that no misunderstanding exists about how to respond during testing:

- Tell the client that earphones will be placed on the head and that tones will be presented at different frequencies, to one ear at a time
- Explain that the purpose of the test is to determine the hearing threshold level *i.e.* the level at which he/she can just hear the tone
- Tell the client to respond by pressing the button or lifting his/her finger as soon as he/she hears the tone
- The tone is initially be presented loudly so that the client hears it properly
- Then the sound is presented more and more softly
- He/she must release the button or drop the finger as soon as the tone is no longer audible
- Explain that the tone will then be presented a little louder, and that he/she must respond as soon as he/she hears the tone as before
- It must be understood that the button must be pushed or the finger lifted every time the tone is heard
- Ask whether he/she is conscious of the fact that one ear may perhaps hear better than the other. If this is the case, then testing should commence with the better ear so that when testing is begun in the poorer ear, and it appears that the discrepancy between the ears is >40 dB, a masking noise can be presented to the better ear to prevent the client from hearing with that ear. If the client thinks the hearing is similar in both ears, then testing may be commenced in either ear
- Before commencing the test, ensure that the client understands all the instructions. During the test, continuously check that the client is responding correctly; if not, the test must be stopped to repeat the instructions before continuing the evaluation

How to do a pure tone audiogram

For a beginner it is wise to follow a fixed testing procedure until sufficient experience has been obtained. The following stepwise approach about how to conduct a pure tone audiogram in adults and older children is intended as a guide for beginners. The experienced tester may alter the steps to adapt to the situation and to the client.

Step 1: Connect the audiometer to the power supply and switch it on. Ensure that it is "live" by noting whether the power light is on

Step 2: Properly connect the earphones to the apparatus and place them on the client's head. It is usual to place them in such a manner that the blue phone covers the left ear and the red phone the right ear. Some phones are marked "Right" and "Left". Ensure that the opening of the earphone is positioned directly over the external ear canal; the height of the phones may be adjusted to allow proper positioning. Ensure that hair is not interposed between the earphone and the ear. Insert earphones may also be used (*Figures 3, 4)*

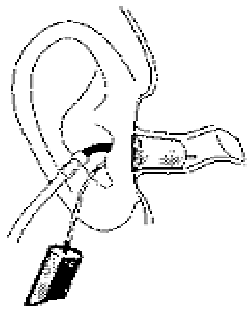


Figure 4: Insert earphones

Step 3: Select the 1000 Hz frequency and set the output switch so that the tone is presented to the better ear. The reason that the test commences with 1000 Hz is because this falls in the middle of the most sensitive area of the hearing spectrum. It is also a clear tone to hear for a person who has never been tested before

Step 4: Initially present the sound at 30 dB HL. If a response is obtained it suggests that 30 dB sound is above the client's threshold. If no response is observed the level is raised to 50 dB and then raised in 10 dB increments until a response is elicited or the limit of the audiometer is reached at that frequency

Step 5: Once a response is obtained the level is lowered in 10dB steps until the client stops responding. It is then raised in 5dB steps until he/she again responds. The sound is at this stage raised and lowered in 5dB steps until the client indicates 50% of the time that he/she hears the sound. The hearing threshold for that specific frequency is defined as the lowest intensity level in dB where a person hears a sound 50% of the time. This level is then transcribed onto the audiogram

Step 6: Switch the frequency to 500 Hz and repeat the above steps. In most cases the difference between the thresholds of neighbouring frequencies does not differ much. Therefore the threshold level at 1000 Hz in *Step 5* is used as the starting point for *Step 6*.

Step 7: Repeat the tests at 250 and 125 Hz

Step 8: Repeat the test at 1000 Hz as a control. If the difference between the initial and repeat measures is $\leq$ 5 dB, it is assumed that the accuracy is satisfactory. If the difference in thresholds between the two tests at 1000 Hz is >10 dB, then the reliability of the test is suspect and it should be repeated from the start

Step 9: Proceed to test at 2000, 4000 and 8000 Hz (intermediate frequencies at 750, 1500 and 3000 Hz are only tested if there are sharp drops *i.e.* $\geq$20 dB) in the audiogram at the octave frequencies [1]

Step 10: Repeat all the above steps on the poorer hearing ear. Determine for every frequency whether it is necessary to mask. When, why and how to mask is discussed later. In general, if the air conduction threshold of the test ear, and the bone conduction threshold of the nontest ear

[1] Interval between one pure tone and another with half or double its frequency

differ by ≥40 dB, then the better ear must be masked to ensure that only the responses from the poorer ear are recorded. The reason for this is that interaural attenuation for air conduction is approximately 40 dB. In other words a sound presented to the test ear must be 40 dB louder than the bone conduction threshold of the nontest ear before that ear hears the sound

Step 11: Masking: A signal of significant magnitude presented to one ear may be perceived by the other ear. This is known as ***crossover of the signal***. Air conduction and bone conduction audiometry are often confounded by such ***crossover or contralateralisation of the signal***.

When crossover occurs one therefore needs to isolate the ear you are trying to test. ***Masking*** is the procedure whereby noise is presented to the nontest ear (NTE) to keep it occupied while the test ear is being evaluated.

Masking concepts to remember:

- ***Test ear (TE):*** Ear of which air or bone conduction threshold is being measured
- ***Nontest ear (NTE):*** Opposite or contralateral ear
- ***Interaural attenuation (IAA):*** Energy lost as sound travels from one ear to the other. It is one of the most important concepts related to masking. Minimum levels of IAA guide the tester as to when crossover is likely to occur. The values differ for air and bone conduction. IAA for bone conduction is approximately 0 dB *(Figure 5)*. Because IAA for air conduction (AC) is about 40dB, there is no risk of crossover when testing air conduction if the difference between the test ear and the nontest ear bone is <40 dB. IAA also depends on the type of transducer being used; levels are set as a function of the transducer type: Supra-aural earphones = 40 dB; Insert ear-phones = 50 - 70 dB; BC vibrator = 0 dB

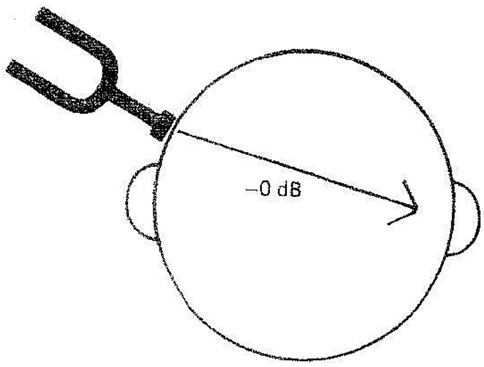


Figure 5: 0 dB interaural attenuation of transcranial bone conduction

- ***Minimum effective masking level*:** The minimum level of narrow band masking noise (NBN) used to prevent cross hearing. A safe level to start masking is AC NTE + 5 dB
- ***When to mask a pure tone AC test?*** When there is a difference of ≥40 dB between the TE AC reponse and the NTE BC response
- ***How much masking for a pure tone AC test?*** AC threshold of the NTE at that frequency plus 5 dB
- ***When to mask pure tone BC?*** When there is ≥10 dB gap between the AC and BC thresholds in the test ear
- ***How much masking for pure tone BC?*** AC of NTE plus 5 dB. If the Bing tuning fork test [2] indicates occlusion (with normal ears or ears with a sensorineural loss the BC becomes louder) a correction factor must be added for the occlusion effect (OE) caused by the earphone on the ear to be masked

[2] Bing tuning fork test involves placing a vibrating tuning fork on the mastoid while the examiner alternately closes and opens the ear canal by pressing inwards on the tragus. A normal person or a person with sensorineural hearing loss hears louder when ear canal is occluded and softer when the canal is open (Bing Positive). A patient with conductive hearing loss will appreciate no change (Bing Negative).

- OE at 250 Hz + 20 dB
- OE at 500 Hz + 15 dB
- OE at 1000 Hz + 5 dB

The starting level in such cases is: AC NTE + 5 dB + OE (only during BC testing)

How to mask

- Tell the client that he/she will hear a "noise" in the NTE which he/she must try to ignore
- He/she must only react to the pure tone ("whistle" or "beep-beep")
- Determine the initial masking level as indicated above
- Present the tone at the unmasked threshold level
- If there is a response, check the masking level by raising the masking level by 5 dB and again by 5 dB
- If there is a response - stop! The threshold is correct
- If there is no response, raise the tone by 5 dB steps until a response is elicited
- Check whether it is correct by raising the masking level twice in 5 dB steps
- Indicate the masked threshold on the audiogram as well as the minimum and maximum masking levels used

Step 12: The ideal masking noise for pure tone testing is narrow band noise, concentrated on the test frequency. If this is not available, wide band white noise may be used for all frequencies.

Step 13: Remember to check, at every frequency, whether it is necessary to mask

Pure Tone Bone Conduction Test

The purpose of a bone conduction test is to determine whether an abnormal air conduction test is due to conductive (middle ear), or sensorineural (inner ear or auditory nerve) pathology. Normal bone conduction with abnormal air conduction indicates a middle ear pathology. When the hearing threshold in both tests is more or less equal, it is likely to be a sensorineural problem.

Bone conduction audiometry is done with an electromagnetic vibrator or bone conductor which is placed on the mastoid bone behind the ear and is held in place with a headband *(Figure 6)*.

Figure 6: Bone conductor vibrator

It must be pointed out to the patient that he/she may hear the tone in the ear which is not being tested, and that this should be reported. Masking usually eliminates this problem.

The following step-by-step procedure for bone conduction testing is advised and is similar to the procedure for testing air conduction

Step 1: First test the ear with the better bone conduction. This can be determined by doing an audiometric Weber test (not 100% accurate....see chapter: [Clinical assessment of hearing with free field voice testing and tuning forks]). The Weber test determines which ear's bone conduction is the best by placing the bone conductor on the forehead and determining in which ear the client is able to hear the sound. Present the sound at 250, 500, 1000, 2000 and 4000 Hz at 20 dB above the best air conduction threshold for each frequency. If the sound is heard centrally ("in the head or middle") it means that the hearing in both ears is equal and bone conduction can be commenced in either ear.

Step 2: Place the bone conductor on the mastoid bone of the ear which was determined to have the better bone conduction threshold, and instruct the client to indicate every time he/she hears the signal by pressing the button. The vibrator should be carefully placed and all interfering hair must be pushed out of the way. The exact placement of the vibrator on the mastoid bone is very important to ensure a good threshold response from the client *(Figure 7).*

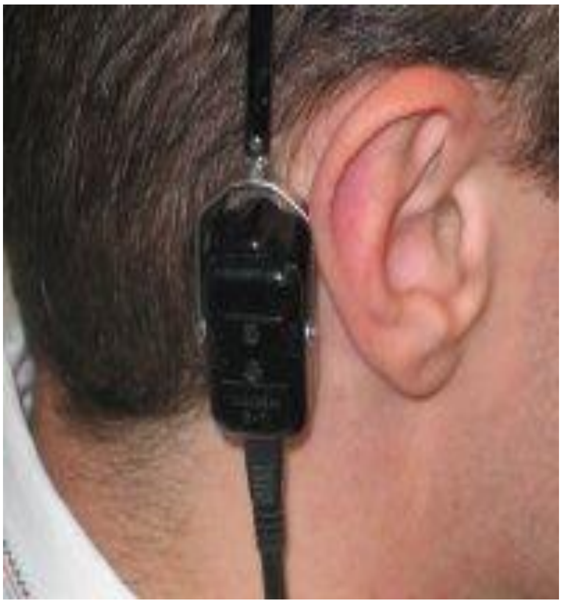


Figure 7: Placement of bone conductor on the mastoid

Step 3: Start testing at 1000 Hz and at a level 10 dB above the air conduction threshold. Determine the bone conduction threshold and decide whether masking is necessary. ***Theoretically it is always necessary to mask when testing bone conduction***, be-cause the interaural attenuation for bone conduction is 0 dB. In practical terms it is only necessary to mask if the bone conduction threshold differs $\geq$10 dB from the air conduction threshold.

Step 4: How to mask? This is similar to the procedure for masking described for testing air conduction

- When masking bone conduction, the bone vibrator is firmly placed on the mastoid bone
- The earphone to be used for masking is placed on the nontest ear with the contralateral earphone placed on the cheek nearest to the bone vibrator to avoid an occlusion effect of the test ear (*Figure 8*)
- Again instruct the client to ignore the noise and only to respond whenever a "whistle" or "beep-beep" sound is heard

Figure 8: Earphone position on bone conduction test ear during masking of contralateral ear

Step 5: Test all frequencies as well as the other (poorer) ear using the same procedure as for air conduction. Retest at 1000 Hz to recheck the initial threshold. Indicate all thresholds with the appropriate symbols on the audiogram *(Figure 1)* and remember also to record the masking level if used. If the bone conduction threshold is below the air conduction threshold, the bone conduction threshold should be recorded at the air conduction threshold (bone-worse-than-air is a physiological impossibility as the same system is tested in both situations)

It is important to obviate certain errors and pitfalls by testers who are not acquainted with the limitations of the testing procedure:

- The tone should not be presented for more than a count of two or three when depressing the "tone presenter switch". ***Tones should be short bursts*** rather than prolonged sounds. Each tone should be presented for about the same length of time, except in situations where the tester may want to check a response to cessation as well as the onset of a tone. It is also better to use a pulsed signal rather than a continuous tone, as a pulsed tone can be more easily discriminated
- ***Audiograms should be done as quickly as possible*** without sacrificing reliability and validity of the threshold. Taking too long to do an audiogram fatigues the subject and causes inaccurate responses
- ***Rushing a test is also undesirable***. Testers should appreciate that some subjects take longer to respond than others. It is essential that one ***allows sufficient time for a response***. Quicker and more definitive responses are often obtained if concise and explicit directions are provided prior to testing
- ***Always ensure that the subject does not directly or indirectly watch*** the control panel of the audiometer and/or the tester
- ***Avoid actions that constitute visual, rather than aural clues*** *e.g.* presenting a signal and then looking up at the client as if to ask if he/she has heard the tone; or moving a hand away from the audiometer after a changing a dial. ***It is poor audiometric testing technique***
- Avoid placing the wrong phone on the ear. Repeatedly check that the ***phones are placed on the correct ear***, that they correspond with the switch on the control panel, and that the threshold is recorded for the ear being tested
- Remember to recheck the threshold at 1000 Hz after the ear is tested for other frequencies, as the initial determination may not have been completely accurate
- If, during the testing of many clients, ***significant hearing losses are found repeatedly at the same frequencies, it is wise to recheck the earphones yourself*** to be sure that nothing has gone wrong during the procedure. Conversely, if all clients appear to have normal hearing, the audiometer may be generating louder tones than the hearing level dial indicates
- ***Avoid rhythmical presentation of the signals***
- Someone with ***tinnitus*** or a ringing noise in the ears may state that the "head noise" is confusing his/her responses. ***If a threshold cannot be determined to the tester's satisfaction, several other methods are available for such patients.*** One is to use two or three short, interrupted tone bursts times, instead of the single tone generally presented to obtain a threshold; this may enable a more accurate response. Such a change in technique and the fact that the subject complains of tinnitus should be noted in the patient records
- Responses may be so varied that an accurate threshold cannot be obtained. In

such cases the test should be terminated and repeated on another day
- Take particular care ***not to press the tone presenter switch down too hard or let it spring back too quickly as this may cause a*** "click", and a subjective response to the "click" rather than to the pure tones

Other Special Tests

Special tests are used to determine if pathology is located more centrally such as in cochlea, auditory nerve, brainstem or cortex. Detailed descriptions of these tests are beyond the scope of this chapter. ***The most important of these tests are****:*

- ***Recruitment:*** This refers to a large increase in perceived loudness of a signal in response to relatively small increases in intensity above threshold. Such persons have a small dynamic range and usually indicates cochlear damage
- ***Tone decay:*** This is a loss of audibility of a sound when the ear is stimulated by a continuous pure tone and is usually associated with retrocochlear pathology

Adaptation of Audiometric Techniques to Special Populations

Nonorganic Hearing Loss population

Nonorganic hearing loss is also referred to as *pseudohypacusis*. There are two main types:

1. ***Psychogenic/hysterical deafness*** is a nonorganic problem, and is a psychological rather than deliberately feigned hearing loss
2. ***Malingering*** is deliberate falsification of hearing loss

Signs might should alert one to pseudohypacusis include the origin of the referral, the history, behaviour during interviews, and performance with routine hearing tests. When someone is referred for financial compensation, nonorganicity immediately becomes a concern. Someone with nonorganic loss may describe all the expected symptoms like vertigo, tinnitus *etc*. The manner in which information is volunteered may also raise suspicion *e.g.* exaggerated postures, overreliance on lipreading *etc*.

Geriatric population

Hearing function decreases with age and is known as presbyacusis. It is typically bilateral, symmetrical, high frequency sensorineural hearing loss of otherwise unexplained origin, occurring in an "older" patient. ***When testing the elderly, certain adaptations in technique should be considered:***

- Be patient, though firm and directive during the interview
- Phrase instructions simply and rephrase if necessary
- Elderly clients often tend to wait until sounds are comfortably loud before responding. To get an accurate threshold it is therefore necessary that they be instructed to respond "even if the sound is very faint and distant "
- Make allowances for impaired motor function *e.g.* difficulty pressing a small button because of arthritis
- A collapsed ear canal must be identified and acted upon. A clue may be inconsistent conductive hearing loss as the earphones may collapse (flatten) the ear canals
- Establish direct visual contact if communication via the earphones proves to be difficult

The Audiometric Environment

Reliable test results require a noiseproof environment and reliable equipment that is in good working order.

Audiometric Booth

Audiometric testing is done in an audiometric booth that meets standards the ISO standard *ISO 8253-1:2010*. Several good booths are commercially available *(Figure 9)*. Differences include positions of the doors and viewports, and ventilation systems and sound reduction capabilities.

Figure 9: Typical audiometric booth

- Booths should be noiseproof enough to reduce ambient noise to acceptable testing levels in accordance with *ANSI* (1969) specifications
- Windows and plugs for earphone jacks must be located such that the audiometer can be placed and the tester can be seated so as to see the client without the client being able to see the operation of the audiometer
- The client should not be required to sit in a closed booth for any longer than is necessary because a risk of experiencing claustrophobia. Show the client how to open the door from inside to reduce apprehension
- Give instructions to the seated subject with the door wide open. Only when the actually testing is the door to be closed. If one needs to interrupt the test to attend to an urgent matter, open the door, remove the earphones, and invite the client to leave the booth until the test is recommenced
- Practise the testing procedure until you can do it accurately and confidently, because the patient may become more anxious in the closed booth if he/she senses insecurity or hesitancy on the part of the tester
- Familiarise yourself with the attenuation qualities of the booth as loud sounds, talking, low flying aircraft or street traffic outside the booth will disturb the client. Rather stop the test during such disturbances.

Daily Maintenance Checks

The following tests and inspection should be conducted at the start of every day:

- ***Check all control knobs on the audiometer*** to ensure that they are correctly fitted on their shafts
- ***Check the calibration of the audiometer*** by measuring the hearing threshold at each test frequency of a person with normal hearing and whose hearing levels are known. Recalibrate the audiometer if ≥10 dB variations occur persistently from day-to-day in the normal person's hearing threshold at any test frequency which cannot be attributed to temporary threshold shifts due to upper respiratory tract infection, noise exposure, *etc*
- ***Check the linearity of the hearing level control*** by listening with the earphones while slowly increasing the hearing level from threshold with the tone control set at 2000 Hz. Each 5 dB

step should produce a small, but noticeable increase in level without changes in tone quality or audible extraneous noise

- ***Test the operation of the presented tone*** with dials set at 2000 Hz and 60 dB HL. Present the sound to a normal hearing listener several times and listen if audible noise, such as clicks or scratches can be heard. No additional noises nor changes in test tone quality should be heard
- ***Replace earphone cushions*** that are not resilient or if there are cracks, bubbles, or crevices
- Straighten ***earphone cords*** to remove kinks or knots and replace cords that are worn or cracked
- ***Test the earphone cords electrically*** by listening with the earphones while bending the cords along their lengths with the dials set at 2000 Hz and 60 dB HL. Any scratching noise, intermittance, or change in test tone indicates a need for new cords
- ***Check for extraneous noises***. No noises should be heard while wearing the earphones when the tone control is switched to each test tone
- ***Check the headband tension*** by observing the distance between the inner sur-faces of the earphone cushions when the headset is held in a free, unmounted state. At the centre of its adjustment range, the distance between cushions should be 2 to 3 cm. The headband may have to be bent to achieve the correct setting
- When it is noted that the audiograms being obtained indicate a ***persistent, unexplainable hearing loss at either all or specific frequencies***, stop testing patients and test several ears known to be normal, in order ensure that the ***instrument is properly calibrated***
- ***Audiometers and earphones must be calibrated every 12 months, or whenever equipment is moved.*** (*ISO 8253-1:2010 International Standards Organisation*)

Audiometric inconsistencies

The above information is intended to minimise problems that may arise during testing that causes inconsistent audiometric patterns. The most important of these inconsistencies are:

- Bone conduction thresholds lower than AC thresholds
- Poor test-retest consistency
- Interview-test discrepancy

Such audiometric inconsistencies can be attributed to various factors including problems with the clinician, the client and the equipment.

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Author

Maggi Soer PhD
Department of Speech-Language Pathology and Audiology
University of Pretoria,
Pretoria, South Africa
maggi.soer@up.ac.za

Editors

De Wet Swanepoel PhD
Professor
Department of Speech-Language Pathology and Audiology
University of Pretoria
Pretoria, South Africa
dewet.swanepoel@up.ac.za

Claude Laurent MD, PhD
Professor in ENT
ENT Unit
Department of Clinical Science
University of Umeå
Umeå, Sweden
claude.laurent@ent.umu.se

Johan Fagan MBChB, FCS(ORL), MMed
Professor and Chairman
Division of Otolaryngology
University of Cape Town
Cape Town, South Africa
johannes.fagan@uct.ac.za

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