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ACOUSTIC IMPEDANCE MEASUREMENTS IN AUDIOLOGY

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HULL ROYAL INFIRMARY

Acoustic impedance measurements have made important contributions to audiology in physiology, in diagnostic audiology and in the development of earphones for hearing aids and audiometers.

Physiology

The middle ear provides a coupling between the relatively low impedance at the eardrum and the high impedance of the inner ear at the oval window. The impedance of the inner ear is resistive, derived from the interaction of the mass of the cochlear fluid (perilymph) and the elasticity of the cochlear partition. The ratio of pressure to particle velocity in the cochlea at a point close to the foot-plate of the stapes is approximately 1.12×10^5 Nsm^{-3} (cf water, $\rho c = 1.5 \times 10^6$ Nsm^{-3}). This is about 300 times greater than the characteristic impedance of the air in the meatus - a disparity which is resolved by the action of the middle ear.

If the meatus is regarded as a transmission line, the ideal termination would be $\rho_o c/S = 9.2 \times 10^6$ Nsm^{-5} where S, the area of the meatus is 44 mm^2. The area of the stapedial foot-plate is about 3.2 mm^2 so that looking into the cochlea, the acoustic impedance at the foot-plate is 1.12×10^5)/ $(3.2 \times 10^{-6}$) $= 3.6 \times 10^{10}$ Nsm^{-5}. The lever action of the middle ear osscicles combined with the ratio of the area of the ear drum to that of the stapes provides a volume transformation of 24:1 and on this basis the transformed acoustic impedance of the cochlea would be $3.6 \times 10^{10}/(24)^2 =$ 6.2×10^7 Nsm^{-5}. This is about 7 times greater than the ideal value and would give a transmission loss of 3.4 dB.

The middle ear is, however, not just a simple lever but a mechanism having finite mass, stiffness and friction. Transmission losses therefore occur by reflection at the drum and within the middle ear itself. The way in which these losses depend on frequency is an important factor in determining the frequency dependence of the threshold of hearing.

At low frequencies the middle ear impedance, measured at the drum is dominated by a stiffness-controlled reactance which comes from the elasticity of the eardrum and the tissues which support the ossicles, and from the compliance of the air in the middle ear space. The reactive component diminishes rapidly with increasing frequency but there remains a resistive component derived mainly from the transformed acoustic resistance of the cochlea. This resistance is predominant in the frequency range 1 to 4 kHz but at higher frequencies the mass of the middle ear mechanism makes a significant contribution and gives rise to a small 'positive' reactance.

ACOUSTIC IMPEDANCE MEASUREMENTS IN AUDIOLOGY

Clinical Applications

Acoustic impedance measurements are an established part of clinical audiology and are a useful aid to the diagnosis of middle ear disorders. Auditory and neural mechanisms involving reflex contractions of the middle ear muscles can also be investigated.

For clinical work the required impedance is the acoustic impedance in the plane of the tympanic membrane and it is therefore necessary to compensate for the impedance of the air in the residual volume of the ear canal between the probe of the impedance meter and the surface of the eardrum. This may be done by applying a static pressure difference across the eardrum which stiffens it to the extent that it becomes an acoustically hard surface. The impedance at the probe is then approximately that of a hard-walled cavity having the same volume as that of the meatus between the probe and the eardrum.

Impedance meters for clinical use usually operate at a single frequency (200 or 660 Hz) which is low enough for the sound pressure to be uniform throughout the space between the probe and the eardrum. The impedance of the meatus is then in parallel with that of the eardrum and it is therefore convenient to make measurements in terms of acoustic admittance (Y_a), the real and imaginary components of which are conductance (G_a) and susceptance (B_a). Many impedance meters, however, do not distinguish between the components of admittance but produce an output proportional to $|Y_a|$ or its reciprocal, $|Z_a|$. These instruments are calibrated by placing the probe in a hard-walled cavity and it is then convenient to express $|Y_a|$ in terms of its equivalent volume of air. This is often registered on a scale marked 'compliance', the justification for this error in terminology being that at low frequencies the acoustic admittance of the ear depends largely on the susceptance of the ear and hence on its compliance (B_a/ω).

Useful diagnostic information can be obtained by observing the way in which the acoustic admittance of the ear changes when the static pressure in the external ear is varied. A graph showing this variation in admittance (or impedance or a related quantity) is called a tympanogram. Admittance is greatest when the pressure in the external ear equals that in the middle ear and thus the location of the peak in the tympanogram is a direct indication of middle ear pressure. Abnormally low intratympanic pressure occurs if the ventilation provided by the eustachian tube is inadequate. The magnitude of the peak in an admittance tympanogram, although stable for a given individual, varies considerably from person to person. For normal ears the 2.5 and 97.5 centiles are respectively 0.43×10^{-8} and 1.7×10^{-8} $m^3/Pa.s$. Greater values indicate an abnormally mobile eardrum due perhaps to a break in the ossicular chain, or more commonly to scarring which makes part of the tympanic membrane flaccid. At the other extreme, an abnormally low admittance is evidence of stiffening of the middle ear mechanism due to middle ear scarring, otosclerosis or to the presence of fluid in the middle ear cavity. The latter is a common disorder in children and the widespread use of tympanometry as an adjunct to pure tone audiometry is due largely to its success in diagnosing the condition.

ACOUSTIC IMPEDANCE MEASUREMENTS IN AUDIOLOGY

Acoustic impedance measurements provide a simple non-invasive way of revealing activity of the intratympanic muscles (tensor tympani and m. stapedius) and the availability of impedance meters has made possible extensive investigation of this subject.

Contractions of the middle ear muscles produce small displacements of the eardrum and small changes in the stiffness of the osscicular system. These effects combine to produce impedance changes within an occluded ear, but generally only the increase in stiffness is detectable.

The contraction of the tensor tympani is a transient response to stimuli, such as a sudden loud sound, which startle the listener. The stapedius muscle, on the other hand, is capable of a sustained contraction lasting for the duration of the stimulus. Several different stimuli can elicit activity in the stapedius muscle. The most important of these is sound, either a pure tone or noise. The response occurs bilaterally with acoustic stimulation of either ear and it is usually convenient to stimulate one ear and to detect the response in the other. The level of stimulation needed to initiate the response (acoustic reflex threshold) is closely related to the loudness of the stimulus and is thus an objective measure of this subjective attribute. The existence of a normal acoustic reflex threshold when the threshold of audibility is impaired demonstrates an abnormally rapid growth of loudness with intensity (recruitment).

Earphones

The performance of an earphone can be specified in terms of the sound pressure developed in a standard coupler, but to simulate its performance on a real ear it is necessary that the coupler should present the earphone with the same acoustic impedance as that of the real ear. A further requirement is that the sound pressure at the microphone in the coupler should bear a fixed relationship to the sound pressure at the eardrum, irrespective of the type of earphone under test.

Couplers for testing hearing aid earphones have to simulate conditions in an ear which is occluded by an earmould. In these circumstances the volume of the meatus between the exit of the earmould and the eardrum is much smaller than the corresponding volume for an external earphone. The impedance at the exit of an earmould therefore depends to a greater extent on the impedance of the middle ear. As stated previously, the acoustic impedance at the eardrum is dominated by a stiffness-reactance at low frequencies and the impedance at the earmould is then the reactance of the air in the meatus in parallel with the reactance of the eardrum. As the frequency is increased the reactive part of the eardrum impedance disappears leaving a constant resistive component and with further increase in frequency a mass-reactance appears. Thus the impedance at the earmould changes from that of a cavity which includes the equivalent volume of the eardrum to that of a cavity in which this volume is negligible. This change in impedance occurs fairly rapidly between the frequencies 1 and 2 kHz.

ACOUSTIC IMPEDANCE MEASUREMENTS IN AUDIOLOGY

Seen through the earcap of an external earphone, the impedance of the ear is that of a cavity (the meatus) shunted by the impedance of the middle ear. The cavity formed by the space between the earcap and the pinna is an additional element. The impedance of this arrangement can be represented by an electrical analogue comprising a capacitance C which is shunted by two LCR brances representing the pinna and the middle ear. A high shunt resistance R_1 is added to simulate acoustic leak between the pinna and the earcap.