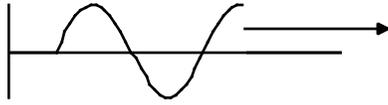


ANATOMY OF THE AUDITORY SYSTEM

Air Borne Sound



Conductive Mechanism

(External Ear)+(Middle Ear)

Inner Ear (cochlea)

Neural Pathways to
the Cortex.

I. The Conductive Mechanism

Problem: Low Z source high Z receptor (cochlea): the air/water problem. When sound traveling in a low Z , media encounters a high Z "barrier" most of the energy is reflected rather than transmitted!

Anatomical Basis for the Middle Ear Transformer Action

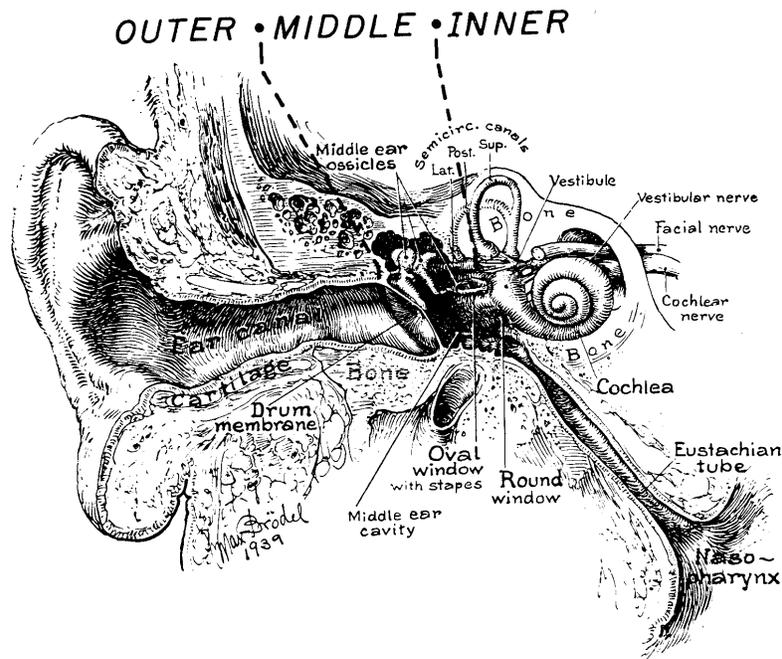


Fig. 1. In this semi-diagrammatic drawing of the ear, the inner ear is shown with the temporal bone cut away to reveal the semicircular canals, the vestibule, and the cochlea. The cochlea has been turned slightly from its normal orientation to show its coils more clearly. The opening for nerves through the bone to the brain cavity of the skull is quite diagrammatic. The Eustachian tube actually runs forward as well as downward and inward.

(1) Auricle - External ear; in man it helps in the localization of sound. In lower animals it is under muscular control and the sound pressure level (SPL) in the external canal is a function of its orientation.

(2) External Canal - Varies from 25-35 mm in length; is "S" shaped and has an elliptical cross section with a 6-8 mm long axis in the vertical plane. It consists of cartilage, soft tissue and bone. The lateral 1/3 of the canal has hair and ceruminous glands which produce "ear wax", keeps the canal from drying out, is bitter and noxious. The canal extends from the external ear to the tympanic membrane.

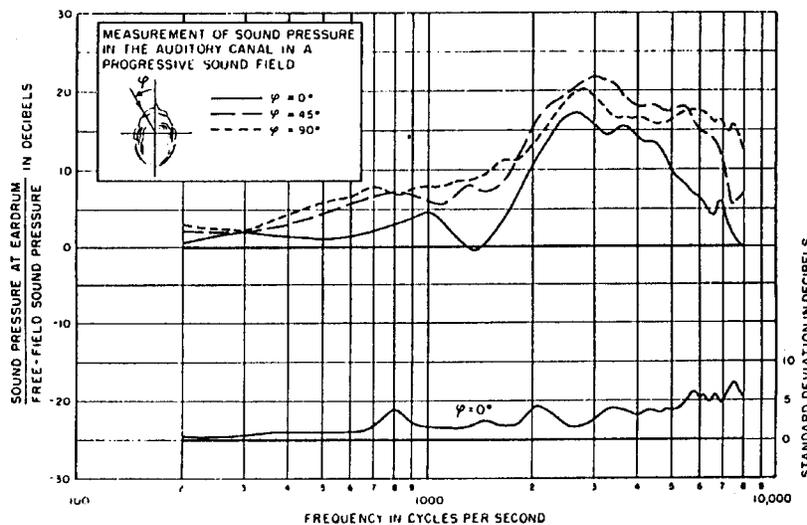


Fig. 2. Sound pressure at the eardrum relative to the freefield sound pressure to illustrate the combined effect of the ear canal. The pinna and the diffraction of the head at different angles of incidence (Wiener and Ross, 1946.)

(3) The Middle Ear - bound by the tympanic membrane laterally and by the oval window at the cochlea medially. The cavity is composed of a central portion, the tympanium ("army drum") and a superior portion the epitympanium. The middle ear contains the ossicles (malleus, incus, stapes) whose function is to transfer air borne vibrations to the cochlea (a fluid filled chamber); Two of the bodies smallest striated muscles, the tensor tympani and the stapedius; and a series of supportive ligaments. The cavity is vented into the nasopharynx via the eustachian tube.

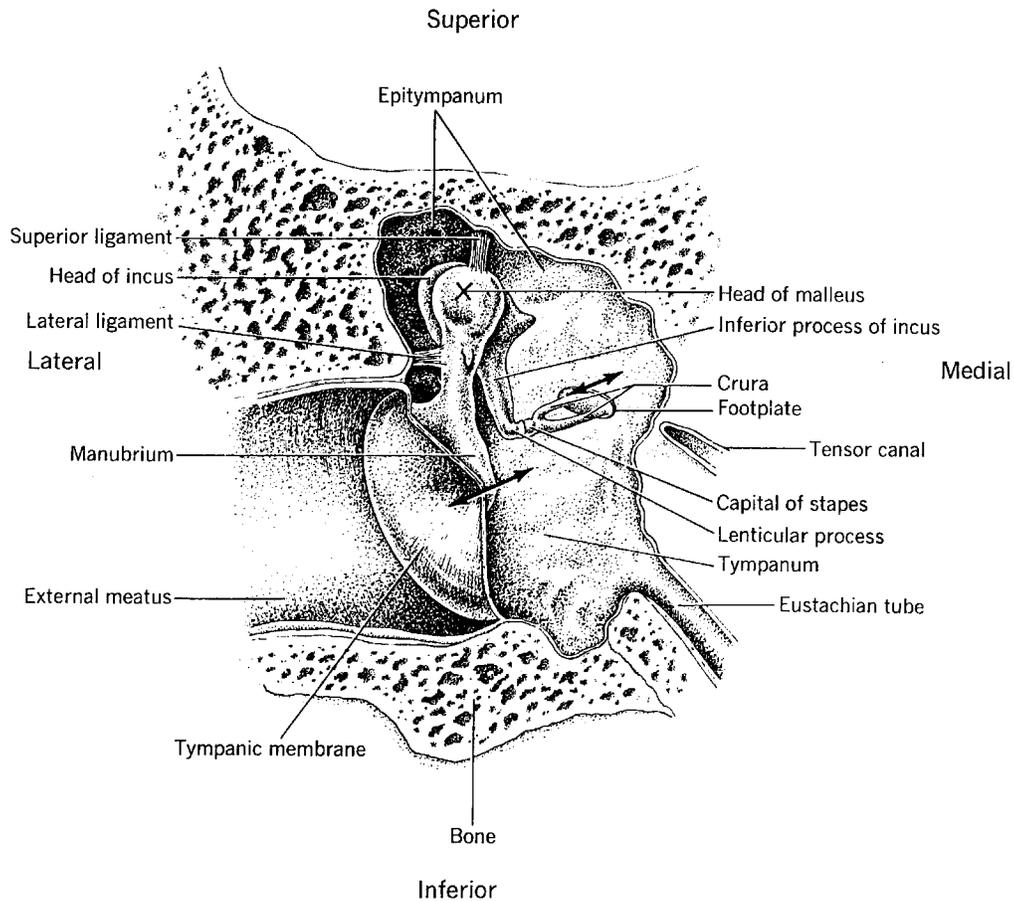


Fig. 3. The general structures of the right middle ear seen in coronal view. The manubrium of the malleus, inferior process of the incus, and the stapes move to and fro along a medial-lateral line. The ossicular chain as a whole oscillates around an anterior-posterior axis through the head of the malleus and incus.

(a) Tympanic membrane - TM - a Trilaminar membrane supported around its circumference by a thickening (fibro-cartilaginous) which is accommodated in a boney groove in the wall of the meatus called the tympanic sulcus. The outer layer of the TM is a thin cutaneous layer, the central portion is composed of radial and circumferential fibers, the inner layer is a mucus membrane. Air borne sound terminates at the TM.

(b) Malleus (hammer) largest of the ossicles, it's connected via the manubrium to the TM. The tensor tympani attached to the manubrium and three ligaments (superior, lateral and anterior) suspend the malleus.

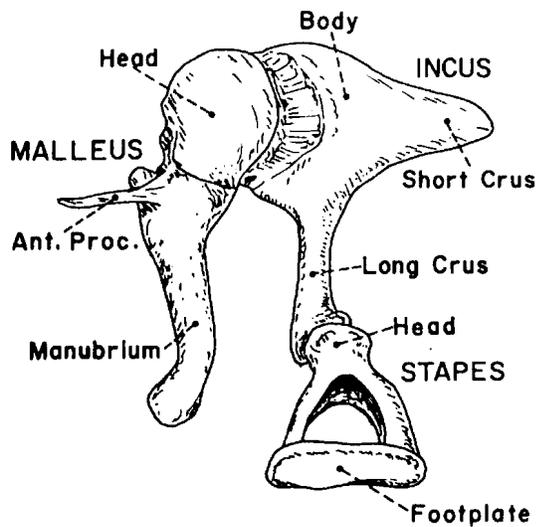


Fig. 4. Medial view of the ossicular chain (right ear), that is from the center of the head (specifically from a position slightly anterior and superior to the ossicles), "looking out."

(c) Incus long process, short process, body (anvil); it articulates via a large balljoint socket with the malleus. A long process tipped with cartilage articulates with the head of the stapes, the innermost ossicle. A posterior ligament attaches to a short process of the incus.

(d) Stapes (stirrup) - consists of a head, neck, two crura, and a foot plate. The foot plate fits into the oval window of the cochlea. It is fastened there by an annular ligament. The head has a concave facet which receives the lenticular process of the incus.

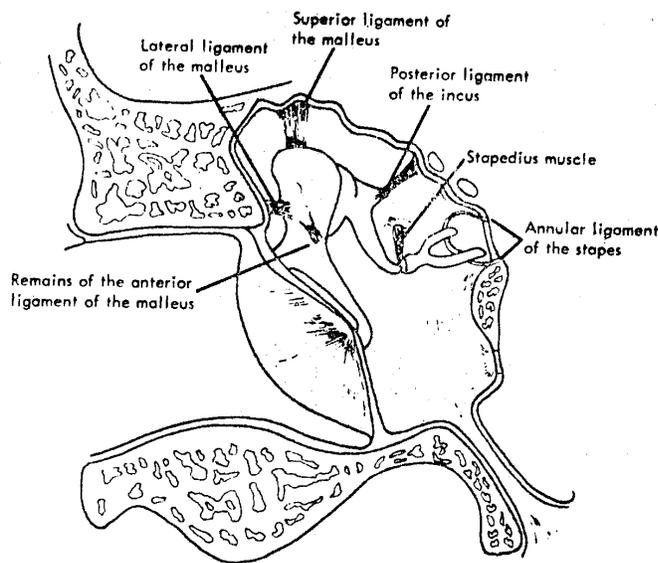
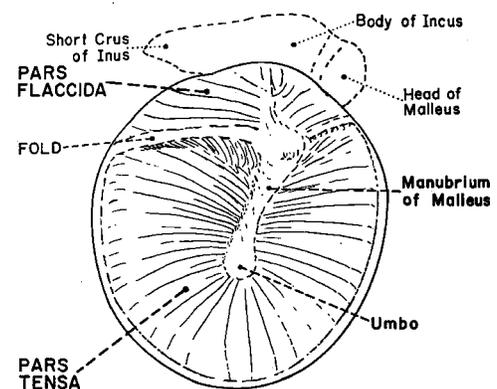


Fig. 5. Schematic illustration of middle ear ligaments, stapedius muscle and tympanic membrane.



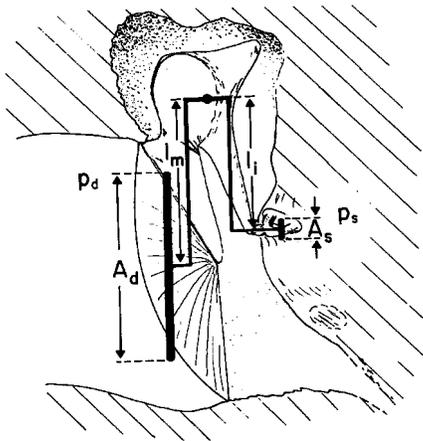


Fig. 6. Components of the middle ear transformer, viewed as a system of pistons connected by a folder lever. A, area; p, sound pressure; l, length. Subscripts: d, eardrum; m, manubrium of the malleus; i, long crus of the incus; s, stapes footplate.

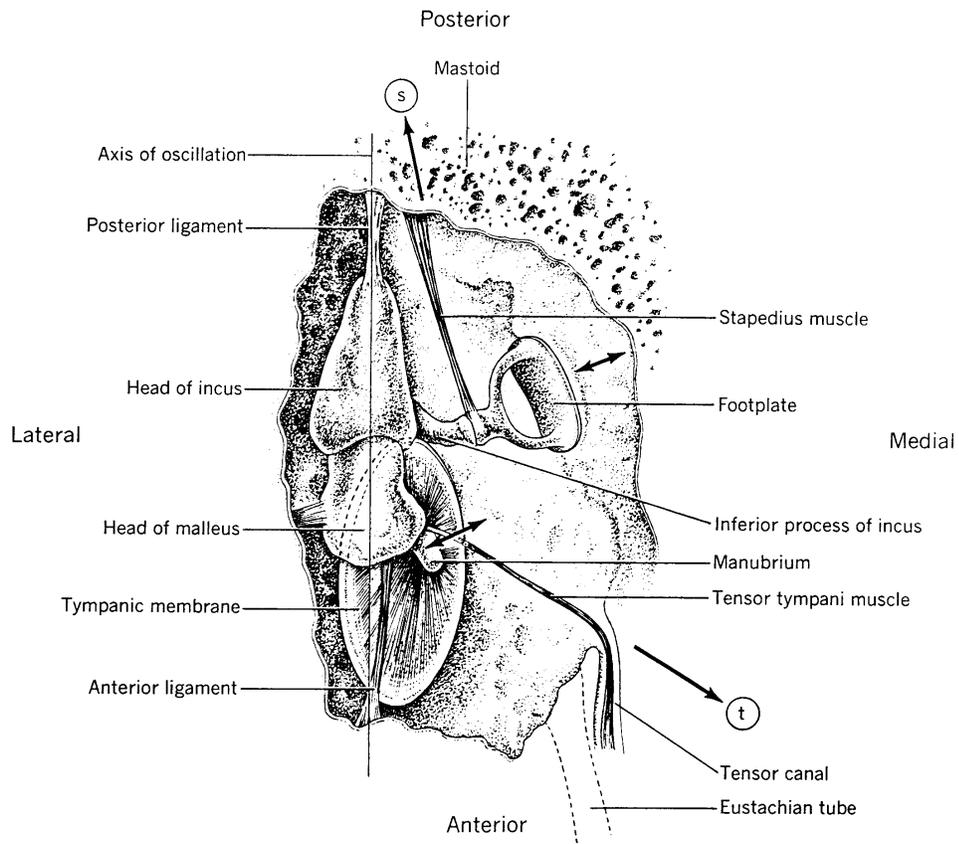


Fig. 7. The general structures of the right middle ear seen in superior view. The manubrium of the malleus, the inferior process of the incus, and the tympanic membrane all are partly obscured in this view by the heads of the ossicles. The arrows (s) and (t) indicate the direction of tension imposed by the stapedius and tensor tympani muscles relative to the axis of ossicular oscillation.

Generally there is little motion in the malleoincudal joint, and the incus and malleus move as one mass. The incus-stapes joint is very flexible. Due to the supports of the ossicular chain, its inertia is very small (i.e., it's a delicately balance system) and its rotational axis is very near the center of gravity.

Middle Ear Muscles: Function (1) Intensity control, or protective, (2) fixation.

(e) Tensor Tympani - Attaches to the upper part of the manubrium of the malleus. Contraction of the tensor draws the malleus inward. This increases the tension in the TM.

(f) Stapedius - Attaches to the neck of the stapes; contraction draws the head of the stapes at right angles to the direction of movement of the ossicular chain.

The muscles contract in response to loud sounds, decreasing the effectiveness of transmission and thus protecting the cochlea. Note: These muscles have a latency of between .01 to .3 sec, hence they provide no protection against intense noise transients. See Figures 10 and 11 for middle ear reflex responses to sound.

The Middle Ear as an Impedance Matching Transformer

There is an impedance mismatch of nearly 4000:1 between the air borne sound and the cochlear fluids. In terms of transmission this amounts to only 0.1% of the energy being transmitted without the intervention of the ossicles, or an energy loss of 30 dB.

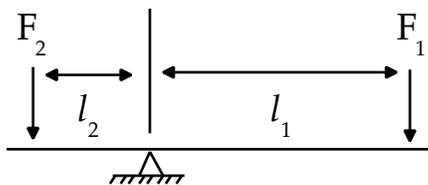
Middle Ear impedance matching transformer:

Rough Mechanical Analysis – See Figure 6

$$\frac{A_d}{A_s} = 19 \quad \text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

$$\frac{l_m}{l_i} = \frac{\text{length manubrium}}{\text{length long crus of incus}} = 1.3$$

The lever arm is a force multiplication device.

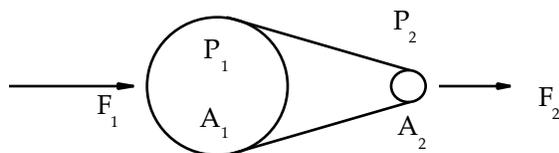


$$F_1 l_1 = F_2 l_2 \quad \text{Thus, } F_2 = \frac{l_1}{l_2} F_1$$

But $l_2 < l_1 \implies F_2 > F_1$ by the amount l_1/l_2

Similarly for Pressure Amplification:

For the Middle Ear $P_s = P_d$ (19) including lever action of the ear increases the factor by 1.3



$$P_1 A_1 = F_1 = F_2 = P_2 A_2$$

$$\text{Thus, } P_2 = P_1 \frac{A_1}{A_2}$$

$$\frac{P_s}{P_d} = (19)(1.3) = 25$$

Thus increase in SPL at stapes is $20 \log_{10} 25 = 28 \text{ dB}$

Alternate Analysis re: Figure 6

$$F_d l_m = F_s l_i \quad F_s = \frac{l_m}{l_i} F_d \quad F_s = 1.3 F_d$$

But $F_d = P_d A_d \quad F_s = P_s A_s$

$$P_s A_s = 1.3 P_d A_d$$

Note: $\frac{l_m}{l_i} \quad 1.3 \quad P_s = 1.3 \frac{A_d}{A_s} P_d$

$$\frac{A_d}{A_s} \quad 19 \quad P_s = (1.3) (19) P_d$$

$$P_s \quad 25 P_d$$

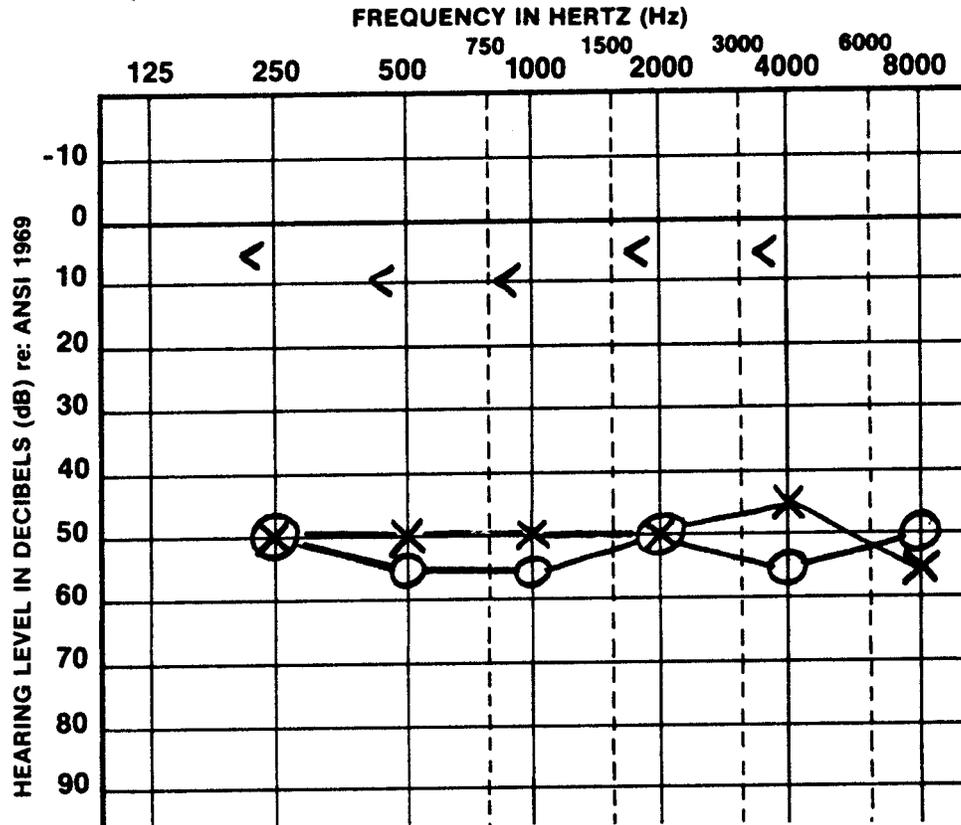


Fig. 8. Audiogram of a person with a disruption of the ossicular chain.

Experiments show losses in sensitivity from 20-50 dB in mammals without middle ear structures: The middle ear provides two mechanisms to increase the pressure at the oval window.

(1) Lever ratio: Measurements show a lever effect on the order of 1.3. This is a consequence of the unequal moment arms of the ossicular chain.

(2) Area ratio: The area of the TM in humans is approximately 60 mm². The stapes foot plate has an area of about 3.2 mm² area ration of about 19:1 the net mechanical advantage is on the order of 25:1 or a possible increase of 28 dB in the pressure seen by the cochlea.

Additional enhancement of the signal is frequency selective and is based upon the resonant characteristics of the external canal and the ossicles.

Studies of the middle ear frequently rely upon measures of the acoustic impedance Z and modeling of the middle ear is performed using electrical analogs derived from a simple damped spring-mass system.

i.e., mass $m \sim$ inductance
 stiffness s (compliance $1/s$) \sim capacitance
 Resistance $R \sim$ electrical resistance.

Equating the driving force to the effects of inertia, friction and stiffness generates a 2nd order differential equation, the solution of which contains a complex term called the Mech. impedance $Z^2 = R_m^2 + j(\omega m - s/\omega)^2$

where $\omega = 2\pi f$

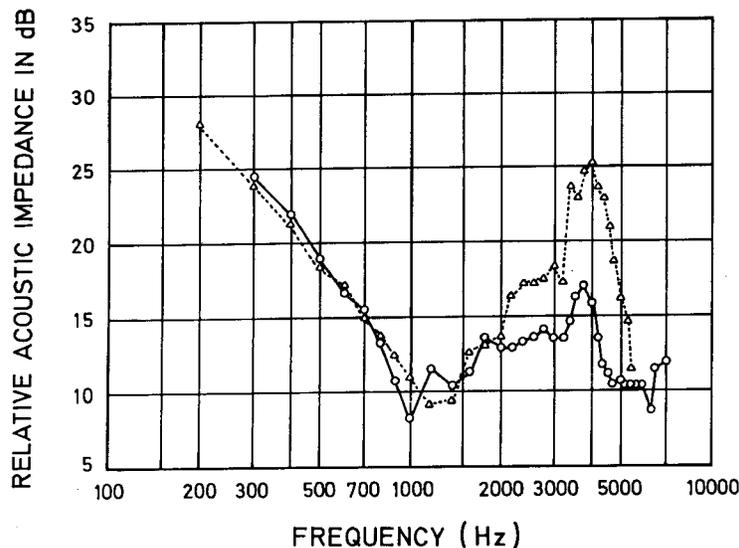


Fig. 9. (a) Acoustic impedance at the eardrum (o) in a cat compared with the inverse vibration velocity of the manubrium of the malleus (Δ) for a constant sound pressure at the eardrum. The reference for the inverse velocity is arbitrary.

Impedance measures are not only used to study the transmission characteristics of the auditory system, but also to diagnose a variety of otological problems.

e.g.: fluid in the middle ear - high resistance
 otosclerosis - high Z ; low compliance
 discontinuity - high compliance

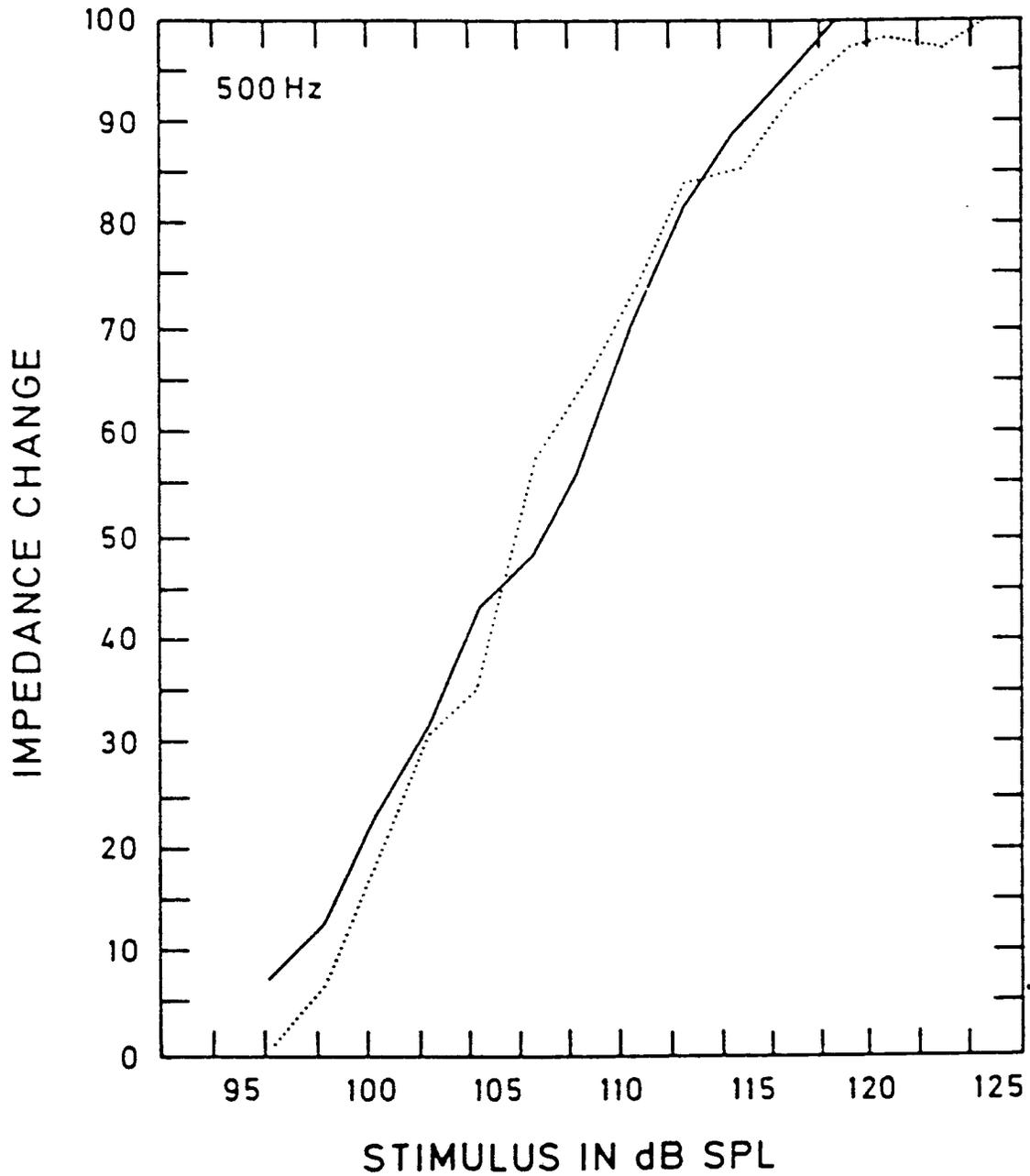


Fig. 10. The response of the acoustic middle ear reflex in a subject with normal hearing measured on two occasions separated by two months. (From Møller, 1962b)

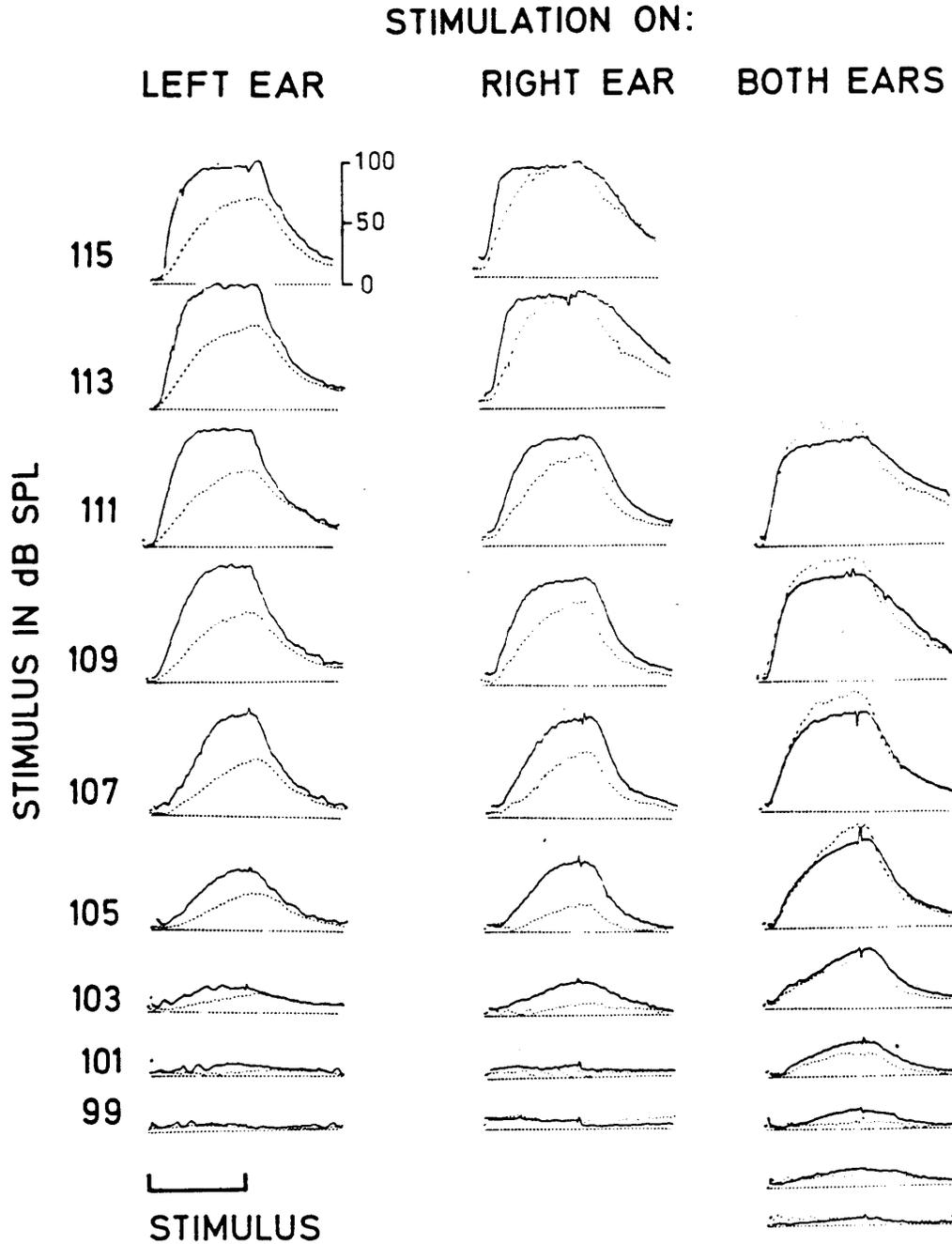


Fig. 11. The change in the acoustic impedance of a human ear as a function of time. The change was recorded simultaneously in both ears in response to stimulation of either left or right ear (monaural) and for stimulation of both ears simultaneously (bilateral). In the two left columns, the solid lines are ipsilateral responses and the dotted lines are the contralateral responses. In the right column (bilateral stimulation) the dotted lines denote the left ear. The stimulus was a 1450 Hz pure tone presented in 500-msec-long bursts. (From Møller, 1962a.)