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PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR
IN DE GENEESKUNDE AAN DE RIJKSUNIVERSITEIT
TE LEIDEN, OP GEZAG VAN DE RECTOR MAGNIFICUS
DR. J.J.M. BEENAKKER, HOOGLERAAR IN DE
FACULTEIT DER WISKUNDE EN NATUURWETENSCHAPPEN,
VOLGENS BESLUIT VAN HET COLLEGE VAN DEKANEN
TE VERDEDIGEN OP WOENSDAG 22 OKTOBER 1986
TE KLOKKE 15.15 UUR

DOOR

CORNELIS JAN BRENKMAN

GEBOREN TE BUNNIK IN 1950

Promotiecommissie:

Promotor:	Prof. Dr. J.J. Grote
Co-promotor:	Dr. W.L.C. Rutten
Referent:	Prof. Dr. A.A. Verveen
Overige leden:	Prof. Dr. H.A.C. Kamphuisen
	Prof. Dr. P.H. Schmidt

In gedachtenis aan mijn vader
Aan mijn moeder
Aan Marijnke, Sandra en Nils

CONTENTS

The investigations reported in this thesis were performed in the Department of Otolaryngology of the Leyden University Hospital.
Mr R. Kamerling, Mr V. Gerritsma, Mr A. v. Wijngaarden and Mr W. Schotel were helpful in the technical and electronic construction of the measuring set-up.
Mr A. v. Ark, Mr N. Siraa and Mr J.W.A. Verburg assisted in the collection of the temporal bones.
Mr B.M.A. v.d. Lans made the figures throughout this thesis.
Prof. Dr. J.H. Drossaart Lulofs gave the author more insight in the ancient greek theories about hearing.
The Twente University of Technology offered the opportunity for the first measurements and cooperated in the installation of the SQUID set-up.

This study was financially supported by the Heinsius Houbolt fund.
The printing was financially supported by Duphar Nederland BV, Amsterdam and Entermed BV.

GENERAL INTRODUCTION

Chronic otitis media, especially when cholesteatoma is involved, can destroy the sound conducting system of the middle ear, resulting in a conductive hearing loss. In addition to the eradication of the disease, middle ear surgery deals with the reconstruction of the impaired sound-conductive system.
To achieve this in the best possible way, knowledge is needed about the anatomy, physiology and sound-conduction properties of the middle ear chain.
To reconstruct the middle ear, autologous- and later homologous implants were originally used. It was known that the direct adherence of a mobile stapes to the tympanic membrane could result in an almost closed audiometric bone-air gap. When there was no direct contact between those two structures, it was possible to interpose a piece of bone between them, to achieve what is called a "columella" reconstruction. This reconstruction could also give very good audiometric results, though such results were unpredictable. In some cases they were excellent, in other cases they were not. Occasionally a good result turned into a bad one without any satisfactory explanation. The problems became more pronounced when the middle ear was more severely damaged, for example when the stapes suprastructure was absent. In these cases it was more difficult to reconstruct the middle-ear function and it was necessary to implant a more complete reconstruction. Sometimes even total homologous middle-ear chains would be employed. This led to many practical and surgical problems, caused by the difficulties of obtaining as well as of implanting these total middle ears. Such problems encouraged the search for artificial materials. Alloplastic materials seemed to be at least of equal value with, and in some cases to have the advantage over, autologous implants (Grote 1981, Grote and Kuijpers 1980, 1983). One of their advantages was that they could be modeled in every desirable form. Thus the question arose, how can this "artificial middle ear" be created so as to obtain the best results according to both sound-conduction criteria and surgical criteria?

The sound-conduction criterion is determined by the sound-transfer characteristics from the tympanic membrane to the stapes footplate. A number of factors can influence these characteristics, for example the rotational axis of the middle-ear chain-which causes a lever action- the middle-ear joints and ligaments, the mass of the middle-ear ossicles and the middle-ear muscles.

The surgical criterion is determined by the surgical skill of the middle-ear surgeon, the applied materials and the severity of destruction of the middle-ear chain. The question in fact became, how simple could the ossicular chain be (surgical criterion), while still yielding very good audiometric results (sound-conduction criterion)?

As described above, the sound-transfer characteristics are influenced by multiple factors. The presence of a rotational axis could well be a very important issue in the design of an artificial middle ear. If such an axis were to be found, one would have to know more about its influence on sound transmission. This knowledge could significantly affect the design of the total alloplastic middle ear.

The aim of this study is to investigate the transfer characteristics of the human middle ear and the role of a possible axis of rotation, in order to improve the results of reconstructive middle-ear surgery, and especially to obtain more precision in the design of devices that are to be implanted.

CHAPTER I

THE ANATOMY OF THE MIDDLE EAR

The middle-ear apparatus lies in a cavity of complex form in the outer, mastoid portion of the temporal bone. Being filled with air and connected to the nasopharynx by the Eustachian tube, it can be divided into hypotympanum, mesotympanum and epitympanum, and the air-cell system of the mastoid. The mesotympanum is the main part of the cavity that lies immediately behind the tympanic membrane. Above it and extending backward and laterally is the epitympanum. The ossicular chain (see fig.1) lies partly in the

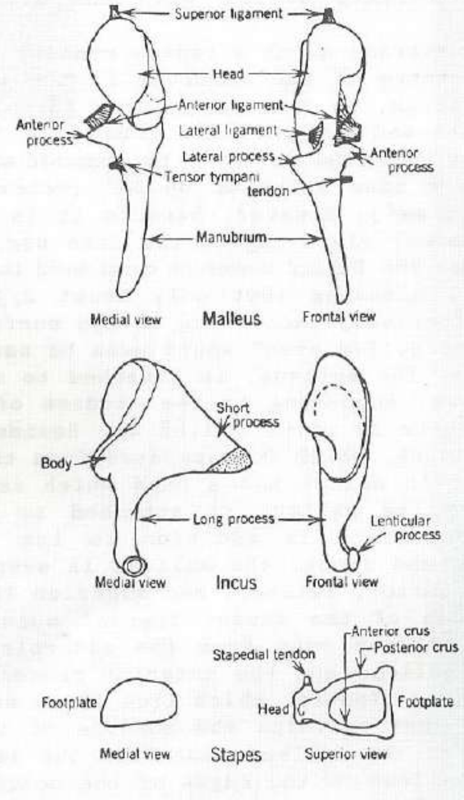

fig. 1 The auditory ossicles from the right ear, shown seperately. (From Wever and Lawrence, 1954).

mesotympanum, but the main part of it is situated in the epitympanum.
The tympanic membrane (pars tensa), which has roughly an elliptical shape, is placed obliquely in the auditory meatus. The pars tensa is composed of three layers: an outer epidermal layer; the lamina propria, consisting of two connective-tissue layers and a fibrous layer; and an inner mucosal layer. Its edges are formed by the fibrous annular ring, which is firmly held in a little groove in the bony walls of the meatus, except in the upper border, where the ring is incomplete. This region is known as the notch of Rivinus. It contains the pars flaccida of the eardrum. It is built up much the same as the pars tensa except that it lacks the highly organized layers of the lamina propria, and contains a higher proportion of elastic fibers in comparison with inelastic (collagen) ones (Lim, 1968). As has been stated by Helmholtz (1868), see chapter II, the tympanic membrane has a conical shape, with the apex pointing medially. Fumagalli (1949) mentioned an apex angle of 120°. The sides of this cone, formed by the ear-drum, are convex outward. Both the apex angle of the cone and the convexity differ with the individual tympanic membrane.
Attached to the membrane along a radius running from the notch of Rivinus to the centre of the membrane is the manubrium, or the handle of the malleus, so that the centre (umbo) of the membrane is situated inward and gives it the form of a flat cone. According to Von Békésy (1941) the surface of the tympanic membrane in adult humans has a mean value of 85 mm^2 (according to Stuhlman (1937) this is 66 mm^2). However, because it is attached to bony structures, it is not vibrating to the same degree everywhere on its total surface. Von Békésy therefore considered the "effective area" as 55 mm^2, assuming that only about 2/3 of its surface would vibrate effectively. According to the surface calculated by Stuhlman, this "effective area" would even be smaller.
The first ossicle, the malleus, is attached to the drum membrane as described above. According to the studies of Kirikae (1960), its weight in adults is 24.91 ± 1.68 mg. Besides the manubrium, it consists of a neck, which is separated from the membrane by an air space (Prussak's space) and a head which is situated in the epitympanum. Here the malleus is attached to the base of the incus (second ossicle). In addition to its fixation to the tympanic membrane and incus, the malleus is suspended from three ligaments, the anterior, lateral, and superior ligaments, as well as from the tendon of the tensor tympani muscle. The anterior ligament of the malleus runs from the anterolateral portion of the neck of the malleus and the anterior process of the malleus to the petrotympanic fissure, which lies in an anterior direction within the fossa that contains the condyle of the mandible. The lateral ligament of the malleus runs from the lateral portion of the neck of the malleus to the edges of the notch of Rivinus. The superior malleolar ligament extends from the head of this ossicle

to the roof of the epitympanum. The tendon of the tensor tympani muscle is attached to the medial side of the malleus near the neck (see fig.2).
In addition to its connection within the epitympanum with the malleus, forming the malleus-incus joint, the incus (weight in adults 27.39 ± 1.03 mg, Kirikae, 1960) is anchored on its short process with the posterior ligament within its fossa in the medial part of the posterior wall of the epitympanum. A superior ligament attaches onto the corpus incudis. As will be described later on, the lateral ligament of the malleus and the posterior ligament of the incus are important structures in determining the axes of motion of the ossicles. Therefore these two ligaments are also called axial ligaments (Von Békésy, 1960). The distal part of the long process of the incus is called the lenticular process and is connected to the third middle ear ossicle, the stapes (average weight 3.38 ± 0.48 mg, Kirikae, 1960). The articulation of these two ossicles (the incus-stapes joint) is diarthroidal because a very small piece of cartilage is situated between these two ossicles. The great complexity of this connection is the principal reason that the function of this joint has not yet been

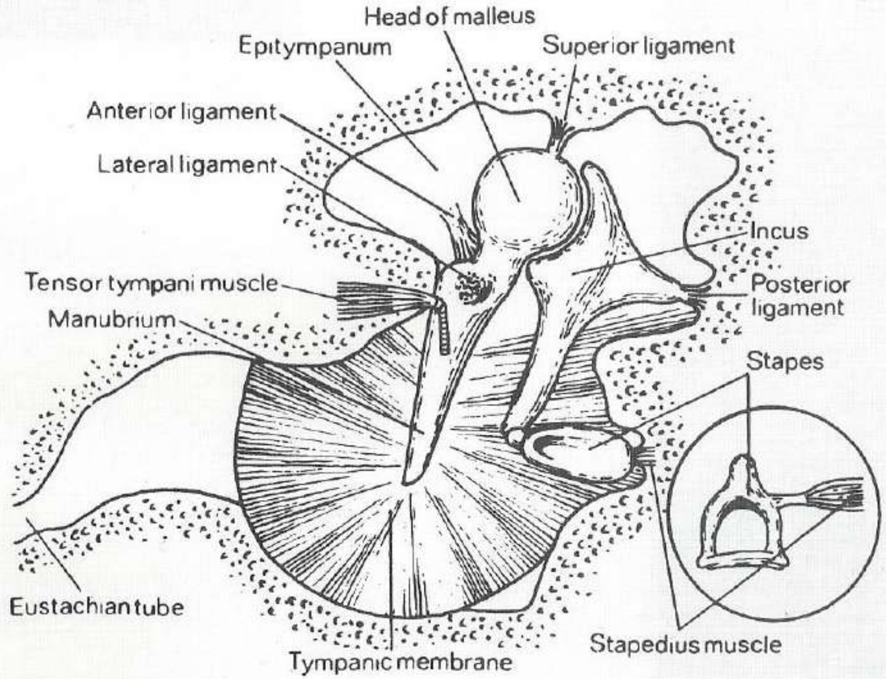

fig. 2 Schematic drawing of the human middle ear (right side) seen from within. (From Møller, 1972).

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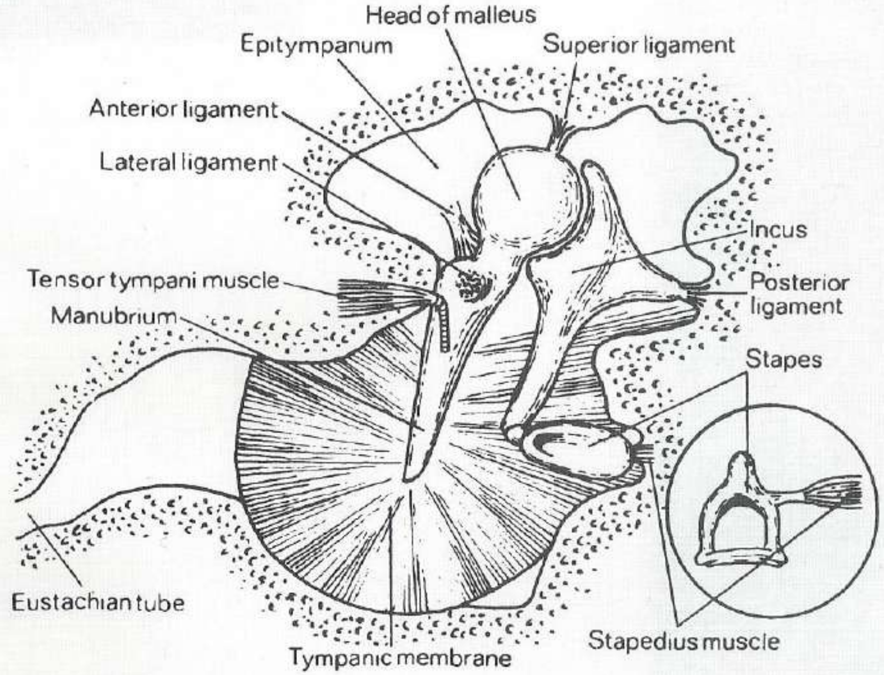

fig. 2 Schematic drawing of the human middle ear (right side) seen from within. (From Møller, 1972).

the cerebral membrane is moist and thick. The moist cannot resound.
Aristotle (384-322) often deals with ears and hearing. In one of the comprehensive chapters (Historia animalium 1.11) in Peck's translation he writes: "Furthermore, there is a part of the head through which the animal hears: it is incapable of breathing, it's called the ear. Incapable of breathing, yes; Alcmaeon is incorrect in saying that goats breathe through their ears. One part of the ear has no special name, the other is called the lobe; the whole consists of gristle and flesh. The natural structure of the interior of the ear is like the spiral-shells: the innermost part is a bone similar to the ear, and to this ultimately the sound penetrates, as into a vessel. There is no passage from this to the brain, but there is a passage to the roof of the mouth, and a bloodvessel passes to it from the brain. (The eyes too are connected with the brain, and each eye is situated upon a small bloodvessel)." There follows a classification of various kinds of ears.
The passage is remarkable. Did Aristotle have some inkling as to the ossicles in the tympanic cavity ? The spiral-shells may be interpreted as the labyrinth, and Aristotle obviously knew about the tube, which in our time is known as the Eustachian tube.

II.2 The first anatomical discoveries

No progress was made in the theory of the action of sound on the ear until the sixteenth century, when the great anatomists of that age, in the course of their comprehensive scrutiny of the human body, brought light to most of the heretofore hidden parts of the ear. In the Renaissance period, Andreas Vesalius (1543) described for the first time the middle ear and the two lateral ossicles as anatomical discoveries. Ingrassia (1546) discovered the third ossicle, the stapes, and Eustachius described the tensor tympani muscle and the tube connecting the tympanic cavity with the pharynx, now known by his name. The second tympanic muscle, the stapedius, was first accurately described by Varolius (1591).

II.3 The first functional descriptions

The first description of the movements of the ossicles is usually ascribed to Politzer, who in 1864 affixed a bristle to the head of the malleus in a temporal bone specimen and took recordings on a smoked drum of the movements of the malleus when the conduction apparatus was stimulated by sound from an organ pipe. In this way

he found a rotational axis running through the anterior process of the malleus.
Mach and Kessel (1874) reported direct visual observations of ear-drum displacements due to static pressures in human cadaver ears, using a simple magnifying lens. With respect to the pars tensa (see chapter I), they found that under a positive pressure in the ear canal the ear drum moved inward and the curvature of the radial fibers flattened; under a negative pressure the curvature increased.
In 1874 Mach and Kessel also used stroboscopic illumination to study the movements of drum and ossicular chain in a fresh human cadaver specimen, with a stimulus with a level corresponding to 149 dB SPL.
Helmholtz (1821-1894) is the founder of modern hearing theories. Based on his very accurate anatomical studies he described in detail the physiology of the middle ear. His "curved membrane" theory (1868) is well known. According to this theory a lever system is formed by the many fibers of the tympanic membrane itself. The theory is based on the typical structure of the tympanic membrane that consists of radial and circular fibers. These two types of fibers are assumed to have different physical properties. The circular fibers must maintain the resting curvature of the tympanic membrane, and the radial fibers must respond to the forces exerted by sound waves by bending. Helmholtz compared each radial fiber of the eardrum with a chain which extends from the edge of the eardrum to the umbo. Its middle portion is relatively free to move. When vibrating, the motion is such that the amplitude of the movement in the centre of the fiber is larger but less forceful, while at the umbo the amplitude is reduced but increased in force. According to this opinion the fiber system constitutes a transformer system of its own, built into the eardrum.
Dahmann (1930) placed small mirrors at various points on human-cadaver eardrums and recorded the angular reflections of a light beam, with the stimulus being a static pressure change of about 60 mm Hg in each direction, equivalent to about 170 dB SPL. He concluded that the middle parts of the tympanic membrane had larger displacements than the malleus. He also investigated the axis of rotation of the middle-ear chain by projecting the malleus on a wall. To achieve this projection, he had to prepare the temporal bone in such a way that only the external ear canal, the tympanic membrane and the malleus were preserved. The rest of the middle ear and the inner ear were removed, resulting in an enormous damage to the middle-ear apparatus (see fig.3). Dahmann thus located the main vibratory axis of the ossicular system along a line from the point of anchorage of the short process of the incus through the anterior process of the malleus, as is shown in fig.4. The effective lever arms run perpendicular from this axis to the point of operation of the forces. The lever arm for the malleus extends to the tip of the manubrium (umbo), and

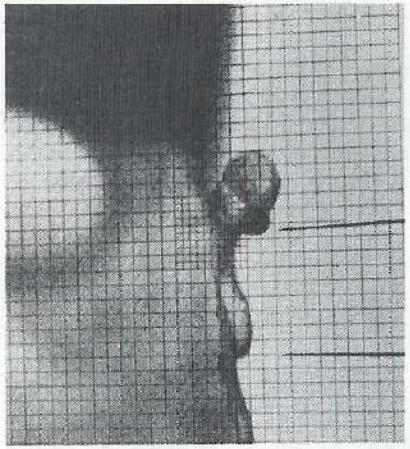

fig. 3 Projection of the malleus-tympanic membrane specimen in profile, onto a scaled wall.

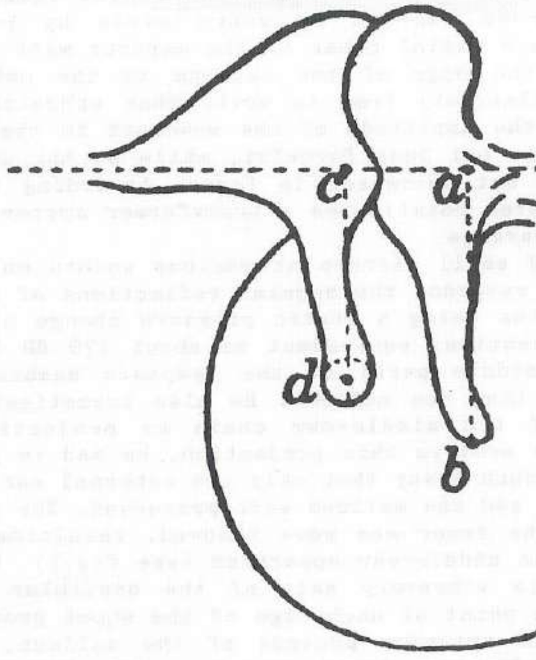

fig. 4 The ossicular lever system according to Dahmann. The line ab is the malleolar lever arm, cd is the incudal arm, and the line through ca is the rotational axis. (From Dahmann 1929, and Wever and Lawrence, 1954).

the lever arm for the incus extends to the end of its lenticular process. He found these two lever arms to differ in length by 1.31 to 1, thus leading to a reduced amplitude and an increased force at the lenticular process.
Stuhlman (1937), after examination of nine specimens of a human middle ear chain, constructed an enlarged scale model and made measurements on it. Assuming the same fixed axis of rotation as Dahmann had described, he measured the lever ratio from umbo to stapes, the amount of which was 1.27:1, very close to the value Dahmann had found. This value, however, was obtained for the situation in which the malleus-incus joint was rigid. When he loosened the coupling between these two ossicles, the axis of rotation -and thus the lever ratio- was altered in two ways, depending on whether the motion was inward or outward, respectively 2:1 and 1:1 (see table I).
Fumagalli (1949, 1951) gave a very accurate description of the possible axes of vibratory movement, based on extensive morphological studies of the middle ears of several species of animals, including man. He assumed that the ossicular system was suspended by ligaments in the middle ear in such a way that it was totally balanced. In this way (as Bárány (1938) also assumed), the accelerating movements of the head did not influence the sound transmission through the middle ear. He concluded that there were two possible axes of movement. One of these, which he called the rotational axis, was the same as the one found by Politzer (1864) and Dahmann (1929, 1930). However, he believed that this axis was operative only for large displacements and commonly only for low frequencies. The second axis, which he called the gravity axis, ran through the anterior process of the malleus and the lenti-

Table I: Lever ratio's of human middle ear ossicles, as obtained from different authors.

Helmholtz		1.5 : 1
Wever and Lawrence (after the concept of Helmholtz)		1.1 : 1
Dahmann		1.31 : 1
Stuhlman (fixed mall-incus joint)		1.27 : 1
(mall-inc joint loosened, movement	inward	2 : 1
	outward	1 : 1
Fumagalli	(gravity axis)	10 : 1
	(rotational axis)	1.3 : 1
Von Békésy		1.3 : 1

cular process of the incus. It served as the functional axis for vibrations of small and moderate amplitudes (see fig.5 and table I).
The results of these earlier investigators were predominantly based on anatomical studies or on scale models or on measurements using a stimulation with extremely high pressure levels. Their concepts are therefore not based sufficiently upon measurements in the physiological range. Modern measuring techniques gave much more insight into the physiology of the middle ear and made a lot of "truths" from the past uncertain.

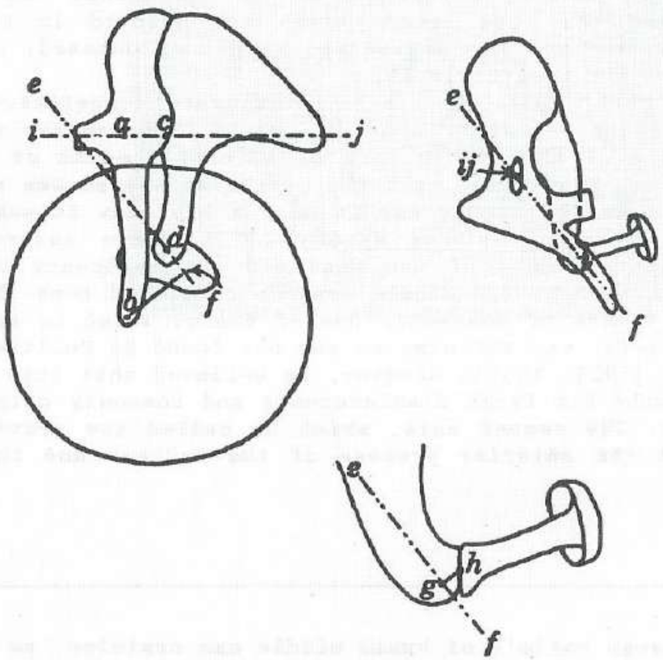

fig. 5 Fumagalli's gravity axis and its lever arms. The axis is the line ef, viewed laterally in the sketch on the left and frontally in the sketches on the right. The force arm is bf and the resistance arm is gh. The rotational axis is shown as ij.

II.4 Modern investigators and techniques

Modern progress in the investigation of middle-ear transmission has been achieved mainly through an improvement in research techniques.

Von Békésy (1941, 1949, 1960) described a method by which it was possible to measure the sound conduction through the middle ear in human temporal bones, postmortem. In this method the tympanic membrane was stimulated by a well-known sound pressure in the external auditory canal, followed by a transmission through the middle ear to the labyrinthine fluid. By placing a microphone in a tube that was cemented with one end over the round window on the middle-ear side, he measured the volume-displacement-amplitude of this membrane. The same method was used by Gundersen (1971) and Kringlebotn and Gundersen (1985), also in human temporal bones. Anderson et al (1962, 1963) used about the same method in a reverse way. They applied the sound to the round window and placed a microphone in the external auditory canal.

This measuring method had two disadvantages. The first was that not only the middle-ear transfer but also a part of cochlear mechanical transfer contributed to the result. Therefore it seems unjustified to draw conclusions about the middle-ear transmission alone. The second disadvantage was the sealing-off of the round window from the influence of middle-ear sound pressure, which could produce a systematic error, since the excursions of the round window are governed not only by the action of the labyrinthine fluid but also by the sound pressure in the middle ear.

Fischler et al (1964, 1966, 1967) measured amplitude and phase spectra at the umbo and at the vestibular side of the stapedial footplate in the same temporal bone preparation, using a capacitive-probe vibration meter. In 15 temporal bones they found a great variability in the transformer ratio of the unloaded middle-ear chain throughout the frequency range. They also observed that the removal of the inner ear resulted in remarkable amplitude changes and shifts of resonances at several frequencies. Because of these problems, their results of middle-ear transfer measurements have to be considered carefully.
Most authors accept one fixed axis - Helmholtz (1868), Dahmann (1929, 1930), Stuhlman (1937), Wever and Lawrence (1954), von Békésy (1941), Khanna and Tonndorf (1972), Tonndorf and Khanna (1972) - all of them assuming a slightly different position.
Wever and Lawrence (1954) assumed that this axis, according to the conception of Helmholtz, was a line running from the end of the short process of the incus to the axial ligament of the malleus.

Von Békésy (1941) confirmed this axis with his capacitive-probe measurements of the tympanic membrane, stimulating within the linear range of the middle ear.
Gundersen and Høgmoen (1976) made a holographic analysis of the malleus-incus complex, and found that the rotational axis moved from the malleus head to the malleus neck when they increased the frequency from the lowest frequencies up to 800-900 Hz. Above that frequency the determination of the axis position was uncertain, but up to 1500 Hz the axis seemed to move back to the malleus head. In this way the changing transformer ratio could be

explained. A disadvantage of their measurement method was the removal of the labyrinthine fluid and the open middle-ear space. Guinan and Peake (1967), using the holographic method, calculated the lever ratio of the ossicular chain of a cat and concluded that there seemed to be a frequency-dependent lever ratio at higher frequencies (above 3000 Hz).
Concerning the malleus-incus joint, almost all authors agree that there is no friction in this joint (which means a rigid connection) within the linear range of sound-pressure stimulation (up to 120-140 dB SPL) (Barany (1938), Kirikae (1960), Møller (1961, 1963), Elpern et al (1965), Cancura (1976, 1980), Gundersen and Høgmoen (1976). At very high sound pressures, and of course in large static air-pressure changes, this joint is not rigid and will serve as a protective mechanism (Kobrak (1959), Kirikae (1960)).

Concerning the incus-stapes joint, Møller (1961) calculated a middle-ear model based on the assumption that there is a situation between a totally fixed and an interrupted incudostapedial joint in the normal middle ear. Guinan and Peake (1967) found no significant difference in amplitude or phase between the incus and stapes displacements of the cat's middle ear. Cancura (1976), in his study of human temporal bones, found no phase differences between incus and stapes displacements between 300 and 1200 Hz, but above 2000 Hz he sometimes measured a phase-lag of 90° or more. Depending on the different frequencies, and probably also depending on the direction of the driving force (long process of the incus), there will be a displacement or a phase lag in that joint. From these few studies it certainly may not be concluded that there is a great similarity between the malleus-incus and the incus-stapes joints.
The movement of the stapes in the human middle ear has been investigated intensively. The early authors described a rotational movement of the stapes around an axis, the position of which differed in the various studies (von Békésy (1939), Kobrak (1959), Kirikae (1960)). Guinan and Peake (1967) found, with more sophisticated techniques, a predominantly piston-like movement of the stapes in living cats. Later this was confirmed in human-temporal-bone studies by Dankbaar (1970, 1972), Gundersen (1971) and Cancura (1977). Høgmoen and Gundersen (1977) found, with the time-average-holography technique, a predominantly piston-like movement of the stapes footplate, with a rotational movement superimposed upon it, the amount of which varied between 1/3 and 1/5 of the piston-like movement.
Therefore it may be concluded from the literature that the stapes vibrates predominantly as a piston in a cylinder.

By this point much was known about the transfer characteristics and about the more detailed parts of the middle ear. However, every measuring method introduced new artifacts such as the opening of the middle-ear cavity, the removal of the inner ear, or direct contact with the vibrating chain. Hillman et al (1964) were the first to use the Mössbauer technique for measuring middle-ear vibrations of human temporal bones. This technique avoids the need of such artifacts. It involves placing a very small gamma-ray source on the vibrating structure and thereby produces a measure of velocity which can then be converted to displacement if the frequency of vibration is known. Johnstone et al (1970), Manley and Johnstone (1974), and Gilad et al (1976) applied the method to measurements of phase and amplitude relations in vibrations of the guinea pig ear in vivo, induced by sound in the normal hearing range. Johnstone and Taylor (1971) compared the middle-ear mechanism of mammalian and non-mammalian animals. In the second group, the animals have what is called a "columella" ear, in which the stapes is directly connected with the tympanic membrane. Up to 4 kHz the amplitude curves of the two different animal groups are virtually indistinguishable, but beyond this the mammalian ear has a very good frequency response, whereas the non-mammals fall off very rapidly. One consequence of this is that the structure and mass of the middle-ear ossicles seems to matter little for frequencies below 4 kHz, and this implies that for the intelligibility of speech, a simple columella prosthesis would make as good an ossicular replacement as any more complicated system.
The Mössbauer method is a very good measuring method but it does not allow human middle-ear measurements in vivo, due to the use of a radioactive source.

The SQUID magnetometer method

A new method was developed and tested, making use of a SQUID (Superconducting Quantum Interference Device) magnetometer (Rutten et al 1982). Using this method, mechanical vibrations are transformed into magnetic flux variations by gluing a small magnet to the middle-ear structure under study. The middle ear is closed with modeling clay after positioning the magnet. The sensitivity of this method is high enough to detect submicroscopic displacement amplitudes of about 10^{-9} meter up to a frequency of about 10 kHz. It also allows the middle ear to be closed and the inner ear to stay intact. The direction of the magnet axis determines the direction of the measurements, thus allowing measurements in different directions (see chapter III, Materials and Methods).
The use of this technique makes it possible to determine the transfer characteristics from umbo to stapes -with a closed middle-ear cavity and an intact inner ear- and to know more about the situation of the axis of rotation of the middle ear.
Though human in vivo measurements are theoretically possible using the SQUID magnetometer, it should be noted that only postmortem measurements are presented in this thesis.

CHAPTER III

MATERIALS AND METHODS

III.1 Introduction

A SQUID magnetometer is a very sensitive magnetometer that can measure very small flux variations. In this study, a tiny rectangular magnet with a known magnetic field (a magnetic dipole) was glued successively to several positions on the middle-ear chain. The tympanic membrane was stimulated by a known sound pressure, causing vibrations of the middle-ear chain together with the affixed magnet. This vibrating magnet causes magnetic flux variations in the lower turn of a second-order gradiometer which can be detected by a SQUID magnetometer. In this way, displacement amplitudes in combination with phase characteristics for several magnet positions can be determined. The method is very sensitive because it can detect displacements on the order of 10^{-9} meter (10Å). After positioning the magnet, the middle ear can be closed. During the measurements, direct mechanical contact with the middle-ear structures (from which amplitude and phase spectra are to be measured) is not necessary.

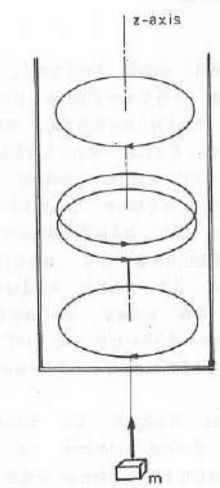

fig. 6 Relative position of the magnet (m) and its magnetic axis (arrow) with respect to the gradiometer axis (z-axis). The gradiometer is mounted into the cryostat (indicated with a double line), which contains liquid helium.

III.2 SQUID set-up

Fundamentals of the SQUID magnetometer method and first experiments have been described earlier (Rutten et al 1982). Validation, modifications and improvements have been reported since then (Rutten et al 1984, 1985, Brenkman et al 1985). Rutten et al (1982) explained that when using a measuring set-up according to fig.6, almost only displacements in the direction of the magnetic dipole axis are measured, and the influence of displacements in other directions can be ignored.
Measurements were performed in a soundproof room which was not magnetically shielded. Mechanical vibrations were transformed into magnetic flux variations by gluing a tiny magnet (Samarium Cobalt$_5$ -SmCo$_5$-, mass 1.05-1.5 mg) to the vibrating point of interest (umbo, processus brevis or anterior crus of the stapes). The SQUID magnetometer set-up (fig.7) consisted of a commercial SHE-330 r.f.SQUID magnetometer, supplemented by an adjustable second-order gradiometer. This assembly was immersed in liquid helium contained in a cryostat which was mounted in a wooden, man-size support. The distance between the sample and the plane of the bottom turn of the gradiometer could be established with great accuracy by means of a heavy hydraulically-adjustable table. The SQUID-output was led via a RF head (SHE 300 RF head) to an electronic processing unit (SHE 330 control unit) and was high-pass filtered (Barr and Stroud EF 3-01, 48 dB/ oct) above 200 Hz and led to a Brookdeal 9505 two-phase lock-amplifier (integration time 300 ms).

Calibration was obtained by measuring the SQUID voltage output in response to the calculated field of a small magnetic coil, which acted as a magnetic dipole and was positioned at several distances, axially centered under the gradiometer. The

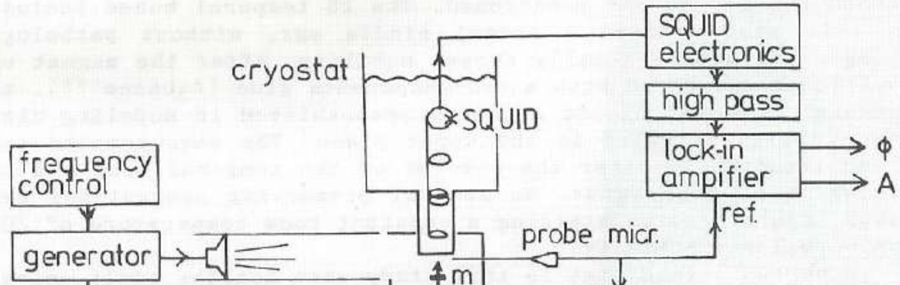

fig. 7 Sketch of the set-up. m is the vibrating magnet, ϕ and A are phase and amplitude output (rms value). Frequency is swept logarithmically from 200 Hz to 10000 Hz in five minutes. Integration time of the lock-in amplifier is 300 msec. Sound level is held automatically constant, range 60-90 dB SPL re 20 μPa.

calibration factor thus obtained was 2.12 x 10 $^{-8}$ Tesla/Volt or 1.15 x 10 $^{-11}$ Wb/Volt.

Sound vibrations were generated by a two-way loudspeaker system mounted in a polyethylene tube, in a semi-closed sound system at 80 dB SPL in the frequency range of 200 Hz up to 10.000 Hz. Frequencies above 2000 Hz were generated by a piëzo-ceramic loudspeaker positioned nearby. Frequencies below 2000 Hz were generated by a magneto dynamic speaker, which was magnetically heavily shielded and positioned 2 meters from the measuring compartment. The frequency was swept logarithmically from 200 Hz to 10000 Hz in five minutes. The integration time of the lock-in amplifier was 300 msec. The sound level was held constant automatically by a Brüel & Kjaer 4134 probe-tube microphone in a feedback loop at the site of the annulus . (This microphone also served as a reference for the lock-in amplifier). Amplitude and phase spectra between 200 Hz and 10000 Hz were written on an X-Y writer and off-line processed by a DEC PDP-11 computer system with a Houston HIPLOT plotter. The latter system corrected for the not-perfectly-flat amplitude- and phase-response of the probe microphone and for the phase characteristic of the high-pass filter.

III.3 The specimen

The experiments were carried out on 18 human temporal bones at the age of death, which varied between 48 and 86 years.
The external ear was removed, except the medial 5 mm, leaving the fibrous annulus intact. The middle ear was reached by widening the Eustachian tube, making an entrance of about 4 mm diameter. In this way the condition of the middle ear could be examined before the magnet was positioned. The 18 temporal bones included in this study showed a normal middle ear, without pathologic changes and with a roughly normal mobility. After the magnet was positioned and fixed with a two-components glue (Aquacem$^{(R)}$), the temporal bone was closed with and encapsulated in modeling clay, the ear drum situated in the upper plane. The measurements took place immediately after the removal of the temporal bone and the placement of the magnet. No special preserving precautions were taken, apart from maintaining a constant room temperature of 20°C and normal air humidity.

The two guinea pigs in this study were healthy adult animals sedated by an intra-peritoneal injection of 0.5 ml/100 g body weight of a 20% aqueous solution of urethane. An incision was made around the pinna, which was then removed. After this procedure the tympanic membrane was visible, with the bony and membranous auditory canal extending laterally from it (length

about 4mm). A very small plate-like piece of Samarium $Cobalt_5$ with a weight of 1.21 mg. was placed on the umbo and "glued" with blood obtained from the animal. The magnetic dipole was placed on the z-axis of the flux transformer (see fig.6).
The death of the animal was caused by an overdose of urethane in combination with Norcuron $^{(R)}$ as a muscle relaxant.

CHAPTER IV

CRITICAL ANALYSIS OF THE MEASURING METHOD

IV.1 General introduction

Validation of the measuring method requires an examination of three critical issues:

1) The mechanical stability of the set-up.
   Are the results a representation of the vibrations of the ossicular chain only, or are there possible artifacts?

2) The mass loading effects of the magnet.
   How great a mass is allowable without causing serious mass-loading effects?

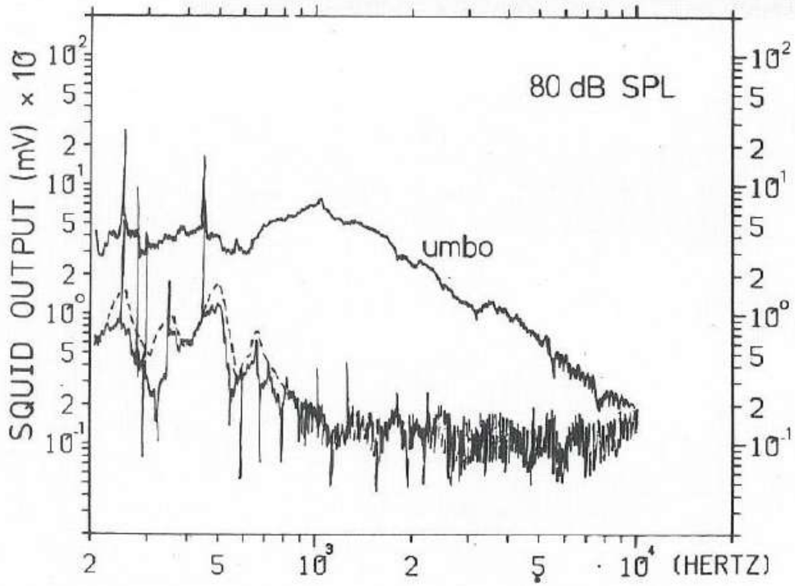

fig. 8 Displacement amplitude for the umbo of one temporal bone at 80 dB SPL. Lower curve : baseline in absence of a magnet, representing mainly environmental magnetic noise. Spikes at 50 Hz or 100 Hz intervals between 250 and 1000 Hz are harmonics of the mains' magnetic field. Dashed baseline curve : as umbo curve but with the magnet glued at the temporal bone, 2mm away from the annular ring.

3) Postmortem changes.
   What are the influences of postmortem changes on the vibration of the ossicular chain, and how can the temporal-bone results be extrapolated into the living situation?

IV.2 The mechanical stability of the set-up

To demonstrate the mechanical stability of the set-up, fig.8 shows an example of an amplitude spectrum, i.e. displacement-rms-amplitude (volts at output A in fig.7), versus frequency for the umbo position, stimulated by 80 dB SPL. The lower curve is the baseline as measured without a magnet on the umbo, and represents background magnetic activity and noise from electrical instruments. The dashed curve shows the baseline when the magnet has been glued to the temporal bone, 2 mm away from the annular ring. It can be concluded that vibratory artifacts are almost negligible.

IV.3 Mass-loading effects of the magnet

IV.3.1 Results

Experiments were performed to determine which mass of the magnet was acceptable for sufficient flux variation at 80 dB SPL without causing serious mass-loading effects.

Figs.9 and 10 show the displacement amplitudes for three different magnet masses, on the umbo and the stapes respectively, stimulated between 200 Hz and 10.000 Hz at 80 dB SPL. For the umbo (fig.9) the two lower masses (1.05 mg and 2.26 mg) give almost equal displacement curves. The highest mass (5.56 mg) gives a displacement increase in the lower frequencies and a decrease in the higher frequencies. The different magnet masses on the stapes (fig.10) give almost equal displacement curves up to 2.16 mg mass. The highest mass (3.66 mg) principally causes a displacement increase in the lower frequencies.

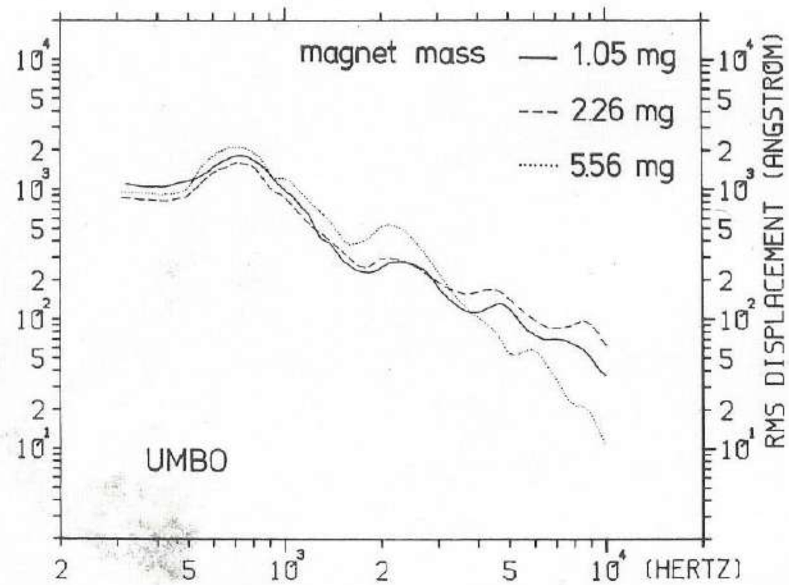

fig. 9 Umbo displacement amplitude versus frequency, in response to a constant input sound level of 80 dB SPL. The effects of three different magnet masses positioned on the umbo are shown.

IV.3.2 Discussion

The two lower masses (1.05 mg and 2.26 mg) applied on the umbo and the three lower ones placed on the stapes (1.05 mg, 1.5 mg and 2.16 mg) give almost equal displacement curves for each position. If the added mass had a real effect on the umbo and stapes displacement curves, it would be very likely that this effect would increase with an increasing mass. Since the mass of the magnet applied in the fourteen temporal-bone measurements (1.5 mg) is well within the range of the masses mentioned above (from which the displacement curves were quite similar to each other), it is very unlikely that its mass-loading effect plays an important role. As expected (see appendix), a higher mass gives a higher amplitude in the low frequencies and a lower amplitude in the high frequencies (fig.9: 5.56 mg, fig.10: 3.66 mg). It appears from our measurements that this change in amplitude occurs between 3000 Hz and 4000 Hz.

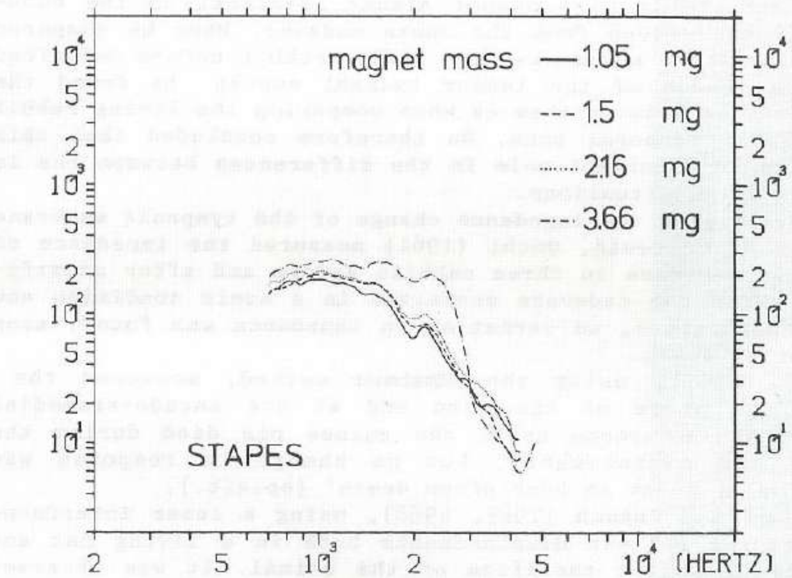

fig. 10 Stapes displacement amplitude versus frequency, in response to a constant input sound level of 80 dB SPL. The effects of four different magnet masses positioned on the stapes are shown.

IV.4 Postmortem changes

IV.4.1 Introduction

There are two main groups of factors to be dealt with in postmortem changes (the separation is somewhat artificial):

a) The factors directly connected with the end of life-functions (labyrinthine pressure, middle-ear muscle function, blood circulation and cellular metabolism). In this paper these effects are called "short-term effects".
b) The factors connected with degeneration of tissue, caused by autolysis and dehydration. These are called "long-term effects".

Animal studies

To study the short-term effects, Gill (1951) used stroboscopic illumination to compare middle-ear-chain movements of rabbits before and after death. He compared these findings with those of human temporal bones removed 12-24 hours after death, and found that the rabbit middle ears removed up to 17 hours postmortem behaved functionally in a manner almost identical to the behaviour of bones removed from the human cadaver. When he compared the ossicular-chain movements in a living rabbit before and after cutting the tendon of the tensor tympani muscle, he found the same differences between them as when comparing the living rabbit with the human temporal bone. He therefore concluded that this muscle plays an important role in the differences between the in vivo and in vitro situations.

To investigate the impedance change of the tympanic membrane immediately after death, Onchi (1961) measured the impedance of the tympanic membrane in three rabbits before and after sacrificing them. With the cadavers preserved in a humid condition and at a low temperature, no variation in impedance was found, even 48 hours after death.

Gilad (1967), using the Mössbauer method, measured the amplitude and phase at the umbo and at the incudo-stapedial joint. "In two or three cases the guinea pig died during the course of the measurements, but no change in response was detected for at least an hour after death" (op.cit.).

Tonndorf and Khanna (1967, 1968), using a laser interferometer, measured mallear displacements both in a living cat and immediately after the sacrifice of the animal. It was observed that the results were not significantly different at least for a period of 1-2 hours. To study the long-term effects, the cadaver was stored in a refrigerator for two days and warmed up again

before testing was resumed. It appeared that the sensitivity of the specimen had decreased by approximately 10 dB in the whole frequency range, but more pronouncedly in the low frequencies.

Human studies

In studying the short-term effects of postmortem changes in human temporal bones we meet serious difficulties. When we want to compare the in vivo and in vitro conditions, we can only compare series of in vivo measurements with series of in vitro measurements. Because of the great variability among individual temporal bones, large groups of measurements are necessary.

Von Békésy (1939), in his study of a small group, found the same damping and resonance of the tympanic membrane in the living and dead human ear, when stimulated by broad-band clicks.

Zwislocki and Feldman (1963) measured the impedance of the tympanic membrane of eight temporal bones. The time between death and the measurements ranged from 2 to 8 ½ hours, with a median time of 4 hours. They found that the acoustic impedance at the eardrum rapidly changed after death. Even a few hours after death they found a much higher impedance than in living, otosclerotic ears with a fixed stapes. These changes occurred especially in the lower frequencies, below 500 Hz.

Peterson and Liden (1970) applied tympanometry to 21 human temporal bones and compared the results with those of 100 living human ears. They found no difference in tympanometric patterns between these two groups. Because they used a higher probe frequency (800 Hz) their results can nevertheless be in agreement with Zwislocki and Feldman (1969, see above), who measured the changes especially below 500 Hz.

Von Bally (1977, 1979) and Fritze et al (1978, 1979) compared the holographic patterns of the tympanic membrane of living humans and human temporal bones and found no differences.

Løkberg et al (1980) measured the vibration amplitude of the human tympanic membrane in vivo using time-averaged interferometry. Their measurements indicate that vibratory amplitudes of the human tympanic membrane in living man are considerably greater than the results of the temporal bone studies found in the literature. However their results have to be judged carefully, because they stimulated using a free sound field from a loudspeaker and measured the sound pressure in front of the entrance of the intact ear canal, and not -as is necessary for an appropriate comparison- near the tympanic membrane.

In describing the short-term effects of postmortem changes, we are dealing not only with muscular, circulatory, and metabolic influences but also with the possible influence of labyrinthine-pressure change after death and its effect on middle-ear characteristics. However, measurements on human temporal bones perfor-

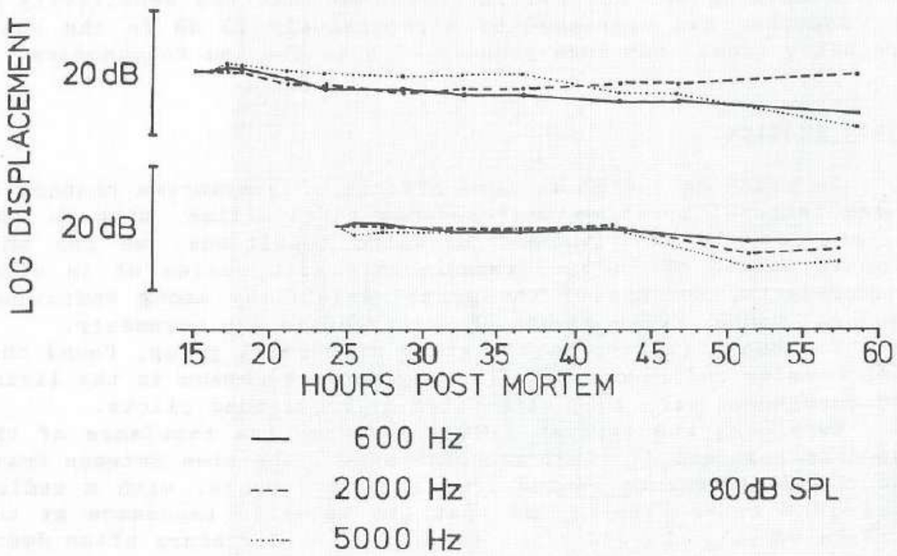

fig. 11 Displacement amplitude of the umbo of two human temporal bones at three frequencies. The vertical scale is logarithmic and shows the relative displacement amplitude changes. On the horizontal scale the hours postmortem are indicated.

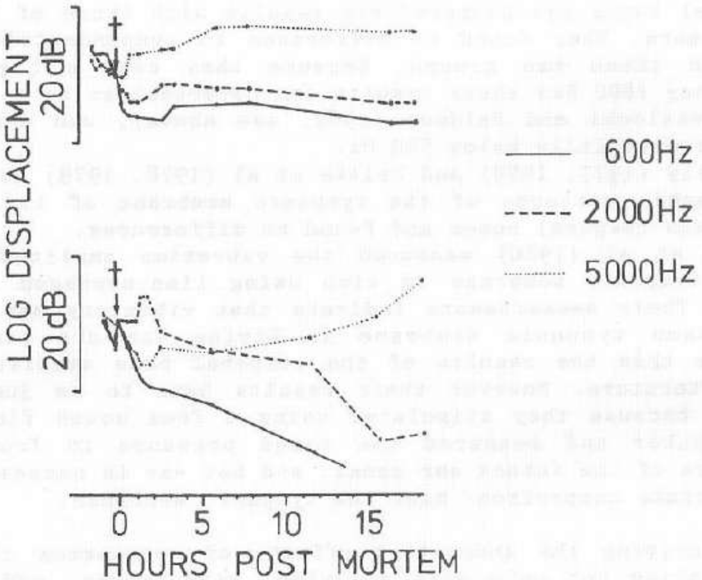

fig. 12 Displacement amplitude of the umbo of two guinea pigs before and after sacrificing, at three frequencies. The cross symbol (†) with the arrow marks the first measurement directly after the death of the animal. The vertical scale is logarithmic and shows the relative displacement amplitude changes. On the horizontal scale the hours postmortem are indicated.

med by von Békésy (1960) and Andersen et al (1962) have shown that an increase of intralabyrinthine pressure did not influence the middle-ear dynamics, up to the point of round- window rupture.

The long-term effects in human middle ears caused by autolysis and dehydration of tissue were studied by von Békésy (1941), Onchi (1961), Elpern and Andersen (1966), Rubinstein (1966), Dankbaar (1972) and Cancura (1980), who investigated the vibrations of the human middle-ear ossicles with different techniques. The duration of time after death in which no changes were observed varied from 40 hours (Elpern and Andersen) to as much as 7 days (Onchi).

IV.4.2 Results

To study the middle-ear changes in human temporal bones caused by long-term effects, the umbo displacement of two temporal bones was measured directly after preparation (12-24 hours postmortem) and at regular intervals up to 60 hours postmortem (fig.11). Apart from a constant room temperature of 20°C and normal air humidity, no special preserving precautions were taken. During the whole measurement time, the specimens were untouched, so that artifacts other than long-term effects were avoided. The measurements started respectively at 15 and at 24 hours postmortem. Fig.11 shows the influence of an increasing postmortem period (horizontal scale) on displacement amplitude (vertical scale) at three frequencies (600 Hz, 2000 Hz and 5000 Hz), stimulated at 80 dB SPL. For both temporal bones the very few changes that were observed occurred within 5 dB up to a period of 45 hours postmortem. After that period the displacements measured at a stimulation frequency of 600 Hz did not change very much, but there was a decrease in the displacements measured during stimulation at 5000 Hz. For the mid-frequency region (2000 Hz), the two temporal bones behaved in different ways. After 45 hours the first temporal bone (upper part of fig.11) showed an increase in displacement amplitude, whereas the second temporal bone (lower part of fig.11) showed a decrease.

To gain more insight into possible immediate postmortem changes, an animal model was chosen.
Fig.12 shows displacement amplitudes versus hours postmortem for two guinea pigs -before- sacrificing, directly after, and up to 18 hours postmortem, stimulated at 80 dB SPL. The measurements started when the animal was alive and continued directly after death (marked with an arrow, ↓). In this case the magnet mass was 1.21 mg. These measurements show a slight variation in displacement amplitude when the animal was alive, but also a direct and much greater change in the first two hours postmortem. After this period the changes are rather little for the first animal (upper

part of fig.12) but much greater for the second (lower part of fig.12). This animal shows a continuous decrease in displacement amplitude for the 600 Hz and 2000 Hz frequencies. The 5000 Hz frequency exhibits a continuous increase in displacement amplitude.

IV.4.3 Discussion and conclusion

Our human-temporal-bone measurements (fig.11) indicate that there is relatively little change in umbo displacement, measured respectively from 15 and from 24 hours, until at least 45 hours postmortem.
As is mentioned above, the transmission data are based on umbo and stapes measurements taken separately. The time between those two measurements was about 15 minutes, in which middle-ear changes caused by long-term effects were minimal. This is demonstrated in fig.11, which reveals no changes within that short a period. It is therefore very likely that the differences in displacement amplitude and phase spectra are caused by the difference in the position of the magnet on the ossicular chain and not by non-controlled or unknown artifacts.
From the literature and from the results described above, it may be concluded that human temporal bones have the same characteristics as the in vivo situation for at least 45 hours postmortem. There is some doubt, however, in the low frequency range (Zwislocki). When changes occur, they start in that region. The very fast changes found by Zwislocki and Feldman (1963) were perhaps caused by their technique of determining the volume of the ear-canal. When their article is read carefully, it appears that they determined the volume of air in the ear canal by filling it with alcohol by means of a calibrated syringe. Due to the fast evaporation of alcohol, the ear canal dried very quickly, which was necessary for the use of the acoustic impedance bridge. It is well known, however, that alcohol, especially in dead materials, causes an enormous desiccation, which possibly would account for the rapid postmortem changes. Nevertheless, as Fischler (1966) describes, there is an increase in acoustic impedance which becomes more pronounced in the low frequency range (found after 5 days ageing of the temporal bone). Concerning the first hours postmortem, the literature gives contradictory and poor results. From our measurements of the two guinea pigs, it must be concluded that these fast changes cannot be completely ignored. We therefore have to be very cautious in extrapolating our results into the living situation.

CHAPTER V

THE TRANSFER FUNCTION OF THE MIDDLE EAR

V.1 Introduction

The transfer function of the middle ear can be determined by measuring displacement amplitudes and phase spectra at the input and output of the system, the tympanic membrane and stapes footplate respectively.

The measuring technique should meet the following demands:

1) it must leave the structure and proper functioning of the ear intact, the middle ear loaded by the cochlea.
2) the technique must be sensitive enough to record displacements on the order of 10^{-9} meter (1 nm = 10 Å).

Because of the great variability among individual middle ears (Fischler et al 1966), it is necessary to compare the in- and output of the same middle ear.

The main purpose of the investigations in this chapter is the measurement of middle-ear input (umbo) and output (stapes) displacement amplitudes and phase spectra in a large continuous frequency-range (200 Hz - 10.000 Hz). The disadvantages of either sealing off the round-window niche or removing the cochlea (see chapter II) are avoided using this measuring method.

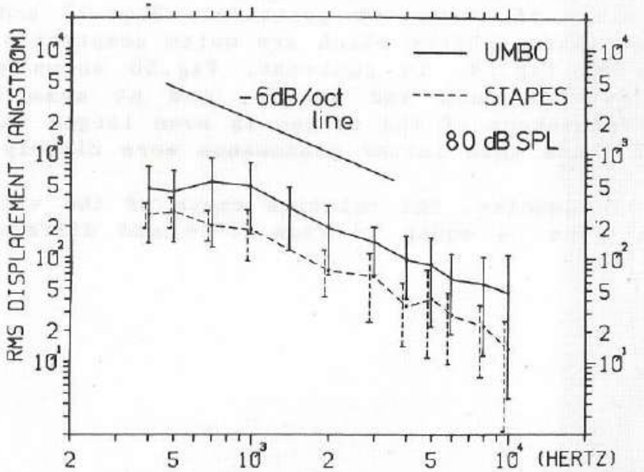

fig. 13 Mean displacement amplitude versus frequency, at the umbo and the anterior crus of the stapes for 14 human temporal bones with the standard deviation (marked as vertical bars). For comparison a -6 dB/octave line is drawn.

V.2 Results

V.2.1 Mean displacement and standard deviation

In 14 human temporal bones displacement was measured at the tip of the malleus (umbo) and on the anterior crus of the stapes. Fig.13 shows the mean displacement amplitude versus frequency at these two positions in response to 80 dB sound input. The continuous line and the interrupted line represent respectively the displacement amplitudes of the umbo and of the stapes positions. The vertical lines represent the standard deviations. In all these displacement values the median was very close to the mean values, which implies a symmetric distribution of these results. After 1000 Hz there is a slope of about -6 dB/oct for both the umbo and the stapes displacement amplitudes.

V.2.2 Amplitude and phase spectra of the individual temporal bones

The mean displacement amplitude curves of fig.13 give a rather coarse impression of the transfer functions of the individual middle ears (as will be discussed later on). Amplitude and phase spectra -in response to 80 dB SPL.- of five individual temporal bones are shown in figs.14 to 18 in the lower part of the figure (continuous line=umbo position, interrupted line=stapes position). The upper part of the figure represents the relative phase of the vibration of these two positions. Figs.14 and 15 show amplitude and phase spectra which are quite comparable with the mean values of fig.13. In contrast, fig.16 shows almost no difference between umbo and stapes, and at some frequency intervals displacement of the stapes is even larger than of the umbo. Fig.17 shows this latter phenomenon more clearly, as does fig.18.
In the low frequencies, the relative phase of the vibration of the two positions is equal in figs.14-16 and differs 180° in figs.17 and 18.

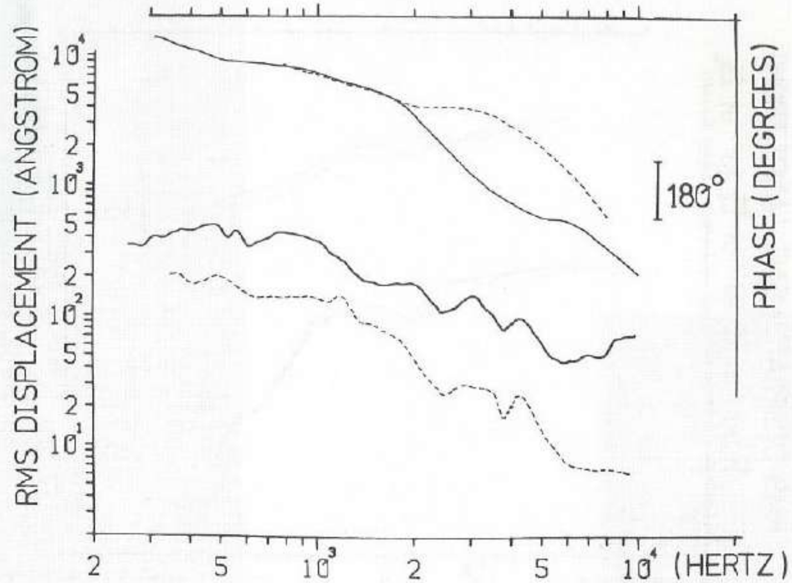

fig. 14

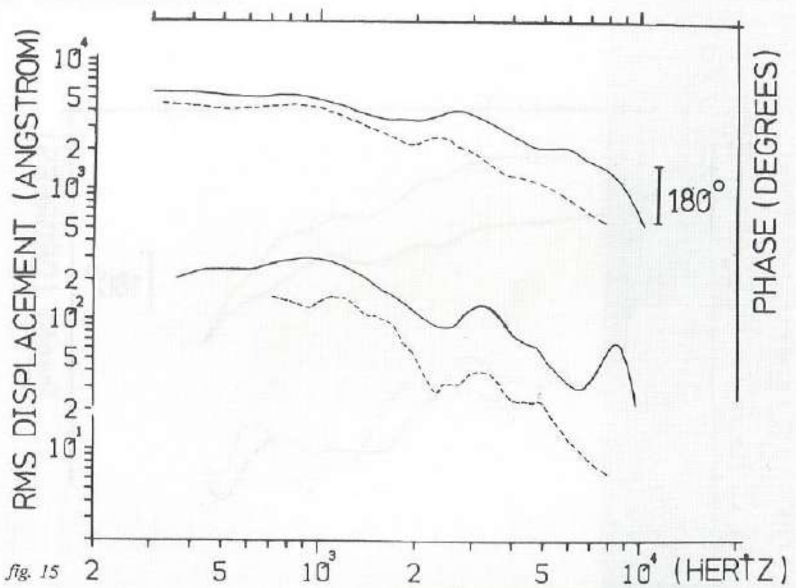

fig. 15

14-18 Amplitude and phase spectra versus frequency, in response to a constant input sound level of 80 dB SPL of 5 human temporal bones (out of the 14 specimens mentioned in fig. 13). In the upper part of the figure the relative phase angle is indicated. The continuous lines represent the umbo position, the interrupted lines represent the stapes position.

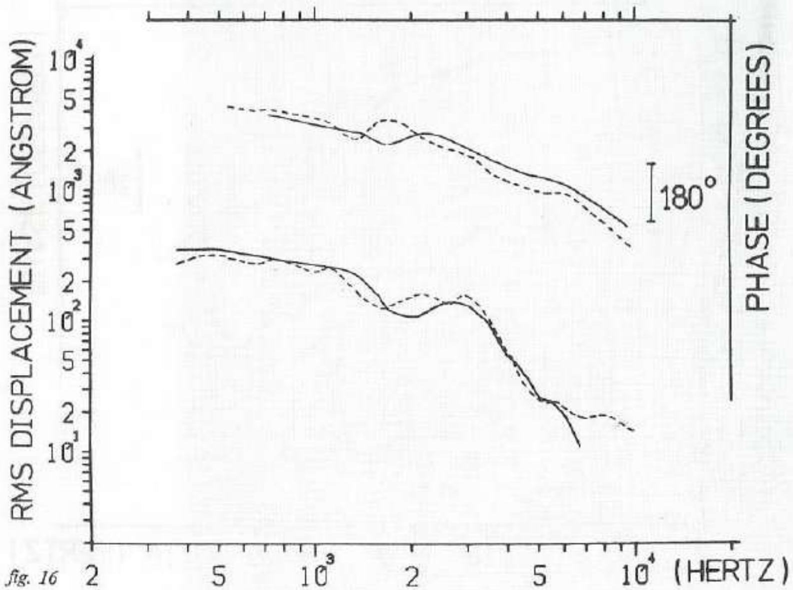

fig. 16

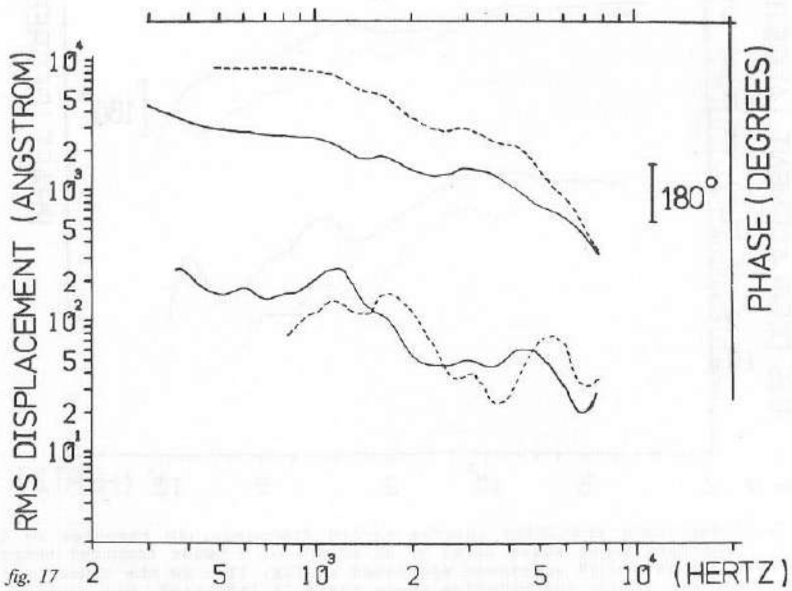

fig. 17

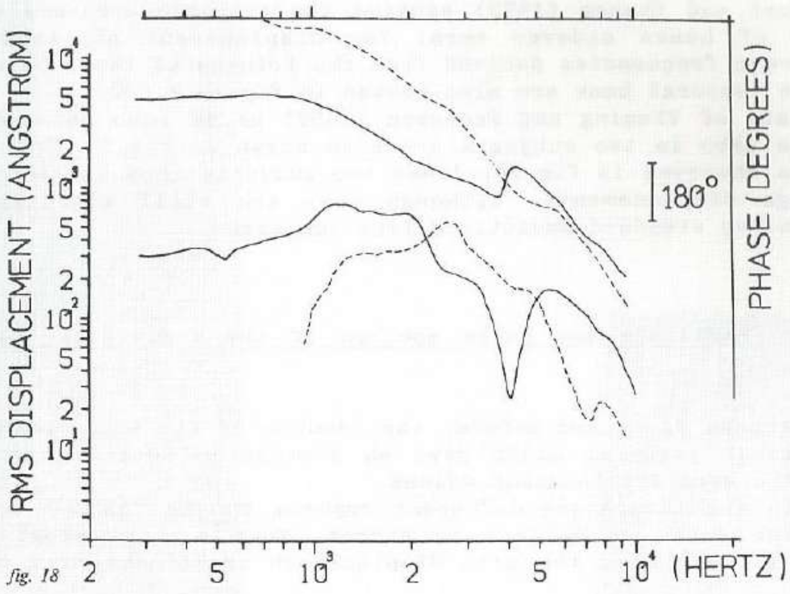

fig. 18

V.3 Discussion

V.3.1 Mean displacement and standard deviation.

These results were compared with the results from the literature. Shaw (1974) collected impedance data from six in vivo studies and calculated their mean values. The impedance (Z) is defined by the ratio of sound pressure (P=80 dB SPL.) to the velocity (V) of the tympanic membrane. Assuming that all points on the "effective" eardrum area of the tympanic membrane have the same velocity, it is possible to convert these average impedance data to eardrum displacements in response to 80 dB SPL sound input, taking an "effective" eardrum area of 0.55 cm^2. The result is drawn in fig.19 as the interrupted line labelled "Shaw". The vertical bar at the left indicates the variability of the mean. The results described in this thesis, compare favorably with Shaw's data, the variability taken into account. Our mean displacement amplitudes are within the standard deviation of Shaw's data, but they are nevertheless above his values. The explanation of this could lay in the fact that Shaw's data are based on in vivo measurements and our data are based on in vitro measurements.

Tonndorf and Khanna (1972) studied the tympanic-membrane vibrations of human cadaver ears. The displacement amplitudes at different frequencies derived from the fringes of their holograms of one temporal bone are also marked in fig.19 (0000).
The data of Vlaming and Feenstra (1982) on in vivo measurements of the umbo in two subjects are also shown in fig.19 (....). As can be observed in fig.19, these two subjects show smaller-than-average displacements, although they are still approximately within two standard deviations from our mean.

V.3.2 Amplitude and phase spectra of the individual temporal bones.

As has been discussed before, the results of the measurements of individual temporal bones give an impression totally different from the mean displacement values.

In the literature different reports can be found about the transfer ratio of malleus to stapes. Most authors obtain this ratio by comparing the mean displacement amplitudes of a series

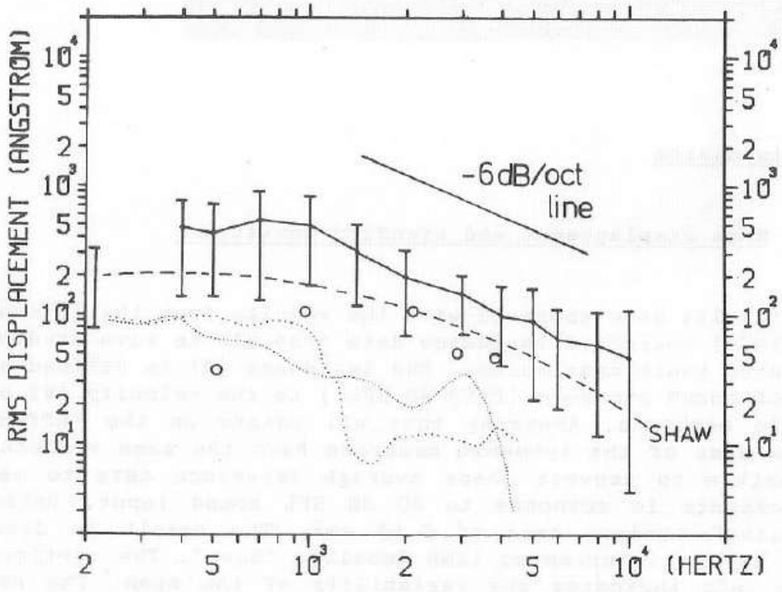

fig. 19 Displacement amplitude versus frequency, in response to a constant input sound level of 80 dB SPL. —— Experimental data of umbo displacements (14 human temporal bones, see fig.13).---- Data of Shaw (1974), i.e. an average of data given by six authors. oooo Data of Tonndorff and Khanna (1972) of the umbo displacements, derived from the fringes of the holograms of one human temporal bone. .... Data of Vlaming and Feenstra (1982) of in vivo measurements of the umbo in two subjects.

of umbo measurements to those of a series of stapes displacement measurements. Others had to destroy the cochlea or a part of the middle ear to compare the umbo and stapes movements within one particular middle ear. Comparing the mean displacement values in the measurements reported in this thesis, we calculate a transfer ratio between 2 and 2.5 (except for one point at 10000 Hz). The individual measurements, however, indicate that this ratio can be smaller than 1 (when stapes displacement is higher than umbo displacement) but also much higher than 2.5 (when umbo displacement exceeds stapes displacement). This changing transfer ratio within the linear range of stimulation has not been mentioned earlier in the literature (see chapter II).

There are two explanations for this changing transfer ratio, which can act in combination:

1) the position of the axis of rotation differs among individuals and also changes as a function of frequency.
2) there is a loss of energy in the joints of the middle-ear chain (malleus-incus joint and incus-stapes joint).

As mentioned in chapter II, Gundersen and Høgmoen (1976) found, in contrast to many other authors, a rotational axis of the middle-ear apparatus which changed with frequency. Guinan and Peake (1966) described the same phenomenon in the cat ossicular chain in the higher frequencies (above 3000 Hz).
The other possible explanation for the differences in umbo and stapes displacement amplitudes could be the loss of energy in the ossicular joints. In chapter II is described that almost all authors agree that there is no friction in the malleus-incus joint within the linear range of sound pressure stimulation (up to 120-140 dB SPL.). There are only a few studies to be found in the literature about the physiology of the incudo-stapedial joint. Cancura (1976) described a phase lag between incus and stapes displacements above 2000 Hz.
These two explanations may also help explain the phase differences between the vibrations of these two positions. This will be discussed extensively in the next chapter.

V.4 Conclusion

It may be concluded that the transfer ratio differs among individuals but also changes as a function of frequency.
The mean displacement amplitudes in our study agree with the results from the literature.
Our results also agree with a change in position of the middle-ear axis as has been described by recent authors (Gundersen and Høgmoen, 1976), and possibly with a displacement loss in the incudo-stapedial joint.

CHAPTER VI

THE ROTATIONAL AXIS OF THE MIDDLE EAR

VI.1 Introduction

In the previous chapter the transfer function of the middle ear was discussed, making use of the SQUID magnetometer method. It was concluded that the transfer ratio differed among individuals and also changed as a function of frequency. From the few references in the literature it seemed that the differences in umbo and stapes displacements in the lower frequencies (up to 1000 Hz) were probably caused by a changing middle-ear rotational axis and in the higher frequencies by a combination of a changing rotational axis and a displacement loss in the incudo-stapedial joint (see discussion of chapter V).
The SQUID magnetometer method makes it possible to investigate the amplitude and phase spectra at different positions on the middle-ear chain, with a closed middle-ear cavity and without opening the inner ear. In this chapter more details about the middle-ear axis will be given.

VI.1.1 Measuring method and calculation of the projection of the rotational axis

With this measuring set-up it is possible to determine the amplitude and relative phase of the vibratory displacements at different ossicular-chain positions. In this chapter the results of measurements at three different positions on the middle-ear chain are described, i.e. umbo, processus brevis (also called short process), and anterior crus of the stapes. The z-direction is the direction of the gradiometer axis (see fig.6). The X-Y plane is the plane of the annular ring of the tympanic membrane. The magnet is positioned in such a way that its magnetic axis is parallel to the gradiometer axis. Only movements in that direction are measured (Rutten et al 1982, see chapter III).
When amplitude and relative phase spectra of the three different positions are known, it is possible to calculate the projection of the rotational axis in the plane of the annular ring of the tympanic membrane. The three measuring points form a triangle because the anatomy of the middle ear does not permit them to be aligned along one line. When one assumes that the middle-ear ossicles have no mutual friction, it implies that umbo, incus and stapes form a "rigid body" and that the triangle has a constant shape. This rigid body can have an axis of rotation, the projection of which can be situated within or outside the projection of the triangle, both projections lying in the plane of the annular ring. Also the projection of the rotational axis can be positioned outside the triangle, and even be indefinitely far outside of it. In this special case there is no rotational movement of the ossicular chain, but a translational (or piston-like) one.
Also with this assumption it is possible to calculate two points of intersection with the sides of the projected "triangle" or with the extensions of the three lines formed by the connection of the three measuring points.
The triangle consists of three lines. For each line the intersection point of the rotational axis can be calculated according to (I), (see below). If the rotational axis would instead intersect an extension of one of these lines, the calculation scheme (II) is valid (see below). With some simple goniometry this calculation can be clarified:

Calculation schemes

(I). Assuming that the projection of the rotational axis intersects the line between two measuring points A and B, this intersection point can be calculated as follows (see fig.20):

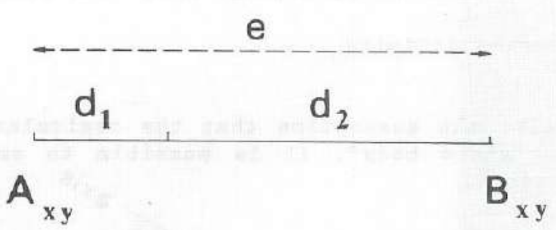

fig. 20 Schematic drawing of the goniometric calculation of the intersection point of the projection of the rotational axis with the line between the projection of the two measuring points A and B, when this axis intersects this line between these two points.

The distance between the projections A_{xy} and B_{xy} in the plane of the annular ring is known and called e. The intersection point divides e in d_1 and d_2. ΔA_{xy} and ΔB_{xy} are the displacements of the A and B positions. The ratio between these two displacements is called v and is proportional to the ratio between d_1 and d_2.

d_1 and d_2 can be calculated using the following expression:

$$d_1 = v\, d_2 = \frac{e\, v}{1 + v}$$

(II): The projection of the rotational axis intersects AB outside A and B or runs parallel with AB (see fig.21).
As mentioned in (I), e, ΔA_{xy}, ΔB_{xy} are known.
In this case e_1 and angle α have to be calculated (see fig.21).

First $\sin\alpha = \frac{d_2}{e_2} = \frac{d_1}{e_1}$, so $\alpha = \arcsin \frac{d_1}{e_1}$

As $\frac{d_1}{d_2} = \frac{e_1}{e_2}$

one has: $\frac{e}{e_1} = \frac{e_2 - e_1}{e_1} = \frac{e_2}{e_1} - 1 = \frac{d_2}{d_1} - 1$

So, $e_1 = \dfrac{e}{\frac{d_2}{d_1} - 1}$

If $\frac{d_2}{d_1} = 1$ then the rotational axis runs parallel with AB, because e_1 becomes infinite.

In summary, with the assumption that the ossicular chain may be treated as a "rigid body", it is possible to create two main groups of movement.

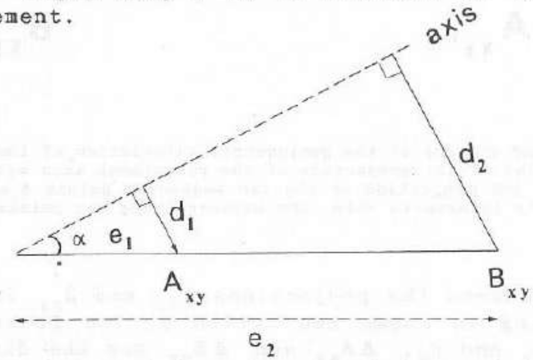

fig. 21 Schematic drawing of the goniometric calculation of the intersection point of the projection of the rotational axis with the line that connects the projection of the two measuring points A and B, when this axis intersects this line outside these two points.

Group a):

There is a rotational movement with a rotational axis, the projection of which can be situated
1) Within the triangle formed by the projections of the three measuring points -in the case that the phase of the vibration of one point of this triangle differs 180° from the other two positions.
2) Outside this triangle -in the case that all points have the same relative phase.

Group b):

There is only a translational (i.e. a piston-like) movement. In this case all three points of the triangle have not only the same relative phase but also the same displacement amplitudes.

VI.2 Results

VI.2.1 Mean displacement and standard deviation at three positions on the ossicular chain.

For 11 human temporal bones displacement was measured at the tip of the malleus (umbo), near the short process (processus brevis) and on the anterior crus of the stapes. Fig.22 shows the mean displacement amplitude versus frequency of these three positions, stimulated at 80 dB SPL. The vertical lines represent one standard deviation. After 1000 Hz there is a slope of about -6 dB/oct for the umbo and the stapes displacement amplitudes.
Up to 2000 Hz the short-process position shows a displacement amplitude, the value of which lies between the umbo and the stapes amplitudes (see fig.22). Above 2000 Hz the short-process displacement amplitude exceeds the umbo amplitude.

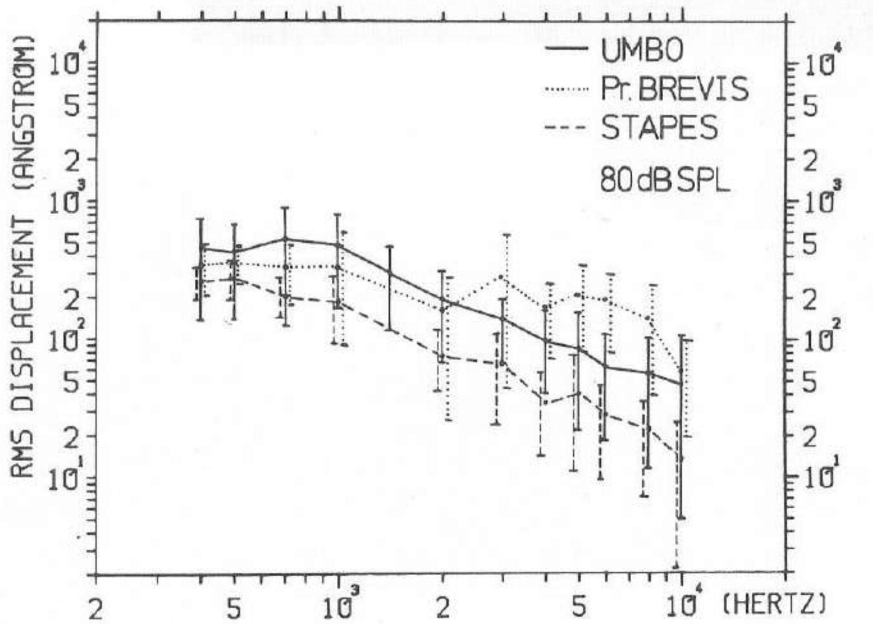

fig. 22 Mean displacement amplitude versus frequency, at the umbo, the processus brevis, and at the anterior crus of the stapes for 11 human temporal bones. Also indicated is the standard deviation (marked as vertical bars).

VI.2.2 Amplitude and phase spectra at three positions on the individual temporal bones.

The mean-displacement-amplitude curves of fig.22 give a rather coarse impression of the transfer function of the individual middle ears. Therefore amplitude and phase spectra for the three positions on each of the eleven temporal bones are shown in figs.24-34. All the middle ears were stimulated by 80 dB SPL.
The lower part of the figure represents the amplitude versus frequency at the three positions (continuous line = umbo position, interrupted line = stapes position, dotted line = short process or pr.brevis position).
The upper part of the figure represents the relative phase at the same three positions.

In almost all measurements, the projection of the rotational axis intersects the sides of the triangle formed by the projections of the three measuring points in the plane of the annular ring (as is indicated in fig.23 with the dotted line). This means that in

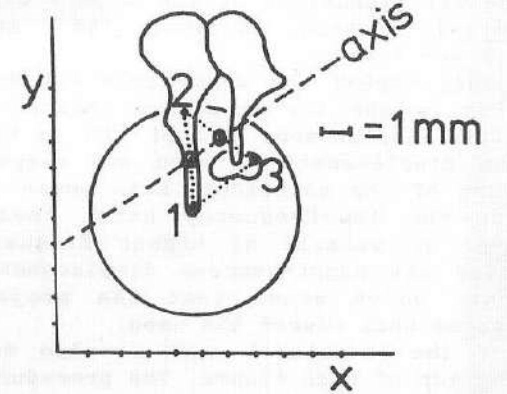

fig. 23 Projection of the ossicular chain into the plane of the annular ring of the tympanic membrane (X-Y plane). The projection of the measuring points (1=umbo, 2=processus brevis, 3= anterior crus of the stapes) form a triangle (dotted line). The projection of the rotational axis (indicated as "axis") intersects this triangle at two points (actually this is the situation in the low frequency region of fig.24). The two intersection points are marked as open circles. The average sizes of the tympanic membrane according to Kirikae (1960) are applied in this projection.

all these cases we are dealing with a rotational movement of the ossicular chain. Depending on the phase relationship of vibrations at the three measuring points in the low frequency region, it is possible to divide the results into three groups:

Group I (figs 24-28), n=5: In the low frequencies, there is a phase-lag of 180° between umbo and pr.brevis. The projection of the rotational axis intersects the hammer handle between the pr.brevis and the umbo.
In fig.24 the displacement amplitude of these two positions is almost equal in the low frequencies, thus giving a point of intersection that divides the distance between umbo and short process into two equal parts. Because the umbo and stapes position have the same relative phase, these two positions are situated together on the same side of the projection of the rotational axis. Because at this frequency their displacement amplitudes are about equal, the projection of the axis is the same distance from the projection of the umbo position as it is from that of the stapes position.
This situation is clarified in fig.23. The triangle formed by the projection of the three measuring points in the X-Y plane, is indicated with a dotted line. The points of intersection (indicated with an open circle) with the umbo- processus brevis line (1-2) and with the processus brevis-stapes line (2-3) both divide these lines into two equal parts. The projection of the rotational axis is drawn as an interrupted line which is running through these two circles (indicated with "axis"). In order to give more insight in the actual dimensions of the middle ear, the average sizes of the tympanic membrane (Kirikae, 1960) are applied for the scale on the X and Y axis.
In the mid-frequency region the phase relation does not differ from the situation in the low frequency region. However, near 1800 Hz there is a displacement dip of the pr.brevis position compared with the displacement at umbo and stapes. This means that the projection of the rotational axis moves in a direction perpendicular to the low-frequency axis, toward the short process, as we go to stimuli of higher frequencies. At the highest frequencies the short-process displacement exceeds the umbo displacement, which means that the projection of the rotational axis moves back toward the umbo.
The projection of the rotational axis is also demonstrated in figs.25-28, at the top of each figure. The procedure to determine this projection is the same as that discussed in the description of fig.24. In the highest frequencies of figs.26-28, the projection of the rotational axis moves beyond the umbo position.

Group II (figs.29-33), n=5: In the low frequencies there is a phase lag of 180° between the umbo motion and that of the stapes.
The positions of the pr.brevis and of the umbo have the same relative phase.
Fig.29 shows this phase behaviour in the low frequency region. At 800 Hz the displacement amplitudes at the pr.brevis and the stapes are equal, which means that the projection of the rotational axis must divide the line between the projections of these two points into two equal parts. The displacement amplitude of the umbo yields a second intersection point, and thus the projection of the rotational axis is determined. At 1500 Hz all three points of the triangle formed by the three measuring points have the same relative phase. This means that the projection of the rotational axis is situated outside this triangle. The ratios of displacement amplitudes at the three measuring points determine its exact position, in the same way as explained elsewhere.
At 2000 Hz the three points still have the same relative phase, but also have almost equal amplitudes. This means that the projection of the rotational axis has moved away infinitely, which implies that the rotational movement has changed into a translational movement. This is indicated in fig.29 with "P" (piston-like movement). Near 4000 Hz there is a relative phase difference of 180° between the umbo and the pr.brevis positions, the displacement amplitudes of umbo and stapes positions are almost equal, and the displacement amplitude of the pr.brevis position is very small. At this frequency the projection of the rotational axis cuts the malleus handle between the pr.brevis and the umbo positions very near the pr.brevis; it lies an equal distance from the projections of the positions at the umbo and the stapes. Near 10000 Hz all three points of the triangle have the same relative phase. This implies that at this frequency all three points are situated at one side of the projection of the rotational axis. The displacement at the pr.brevis position is not even detectable anymore. Therefore the point of intersection with the malleus is situated very close to this pr.brevis position. The relationship between the displacement amplitudes at the umbo and the stapes gives the second intersection point, after which the projection of the rotational axis can be determined.
In figs.30-33 the projection of the rotational axis can be determined in the same way as described above.

Group III (fig.34), n=1: In the low frequency region all three measuring points have the same relative phase. Only fig.34 belongs to this group.
At 600 Hz the projection of the rotational axis is situated outside the triangle formed by the three measuring points. The displacement amplitudes determine its precise location as is described above. In the middle and higher frequencies the position of the axis changes in such a way that it gives a point of intersection with the hammer handle between the umbo and the pr.brevis position.

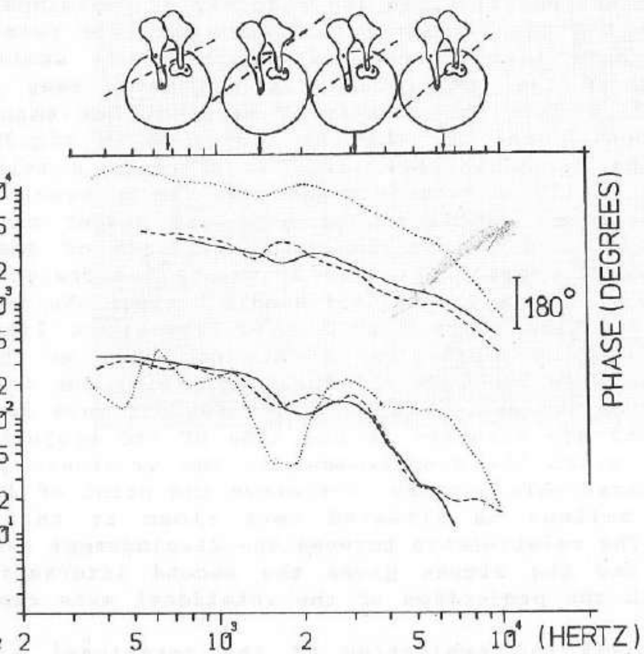

fig. 24

24-34 Amplitude and phase spectra versus frequency, in response to a constant input sound level of 80 dB SPL of 11 human temporal bones. In the upper part of each figure the relative phase angle is indicated. The continuous line represents the umbo position, the dotted line the processus brevis position and the interrupted line the stapes position. Above the figures projections into the X-Y plane (see fig.23) of the ossicular chain together with the three measuring points are indicated. For several frequencies (indicated with arrows) the calculated position of the projection of the rotational axis is drawn.

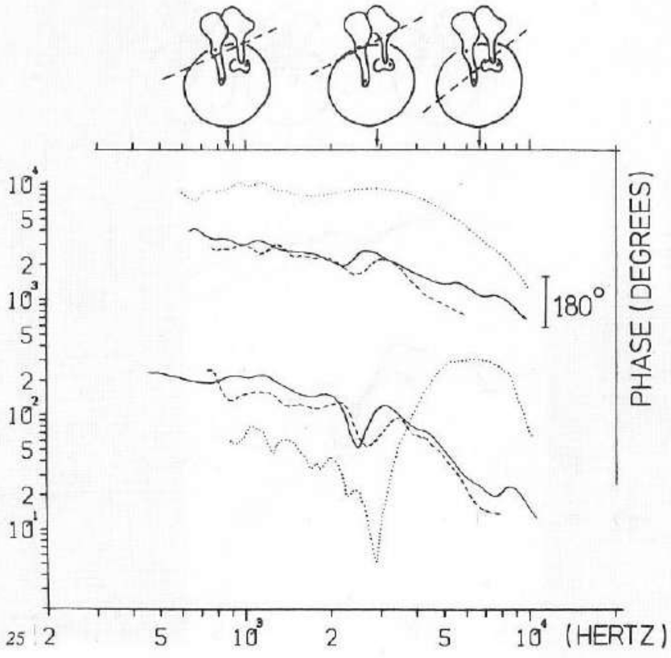

fig. 25

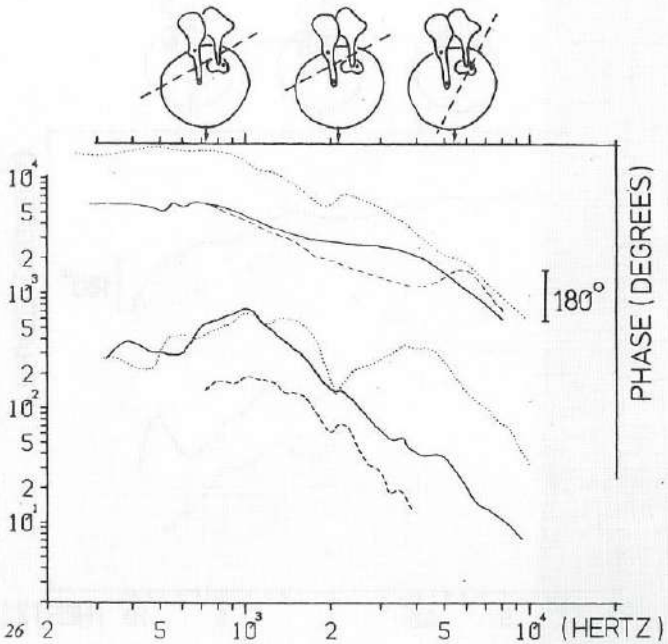

fig. 26

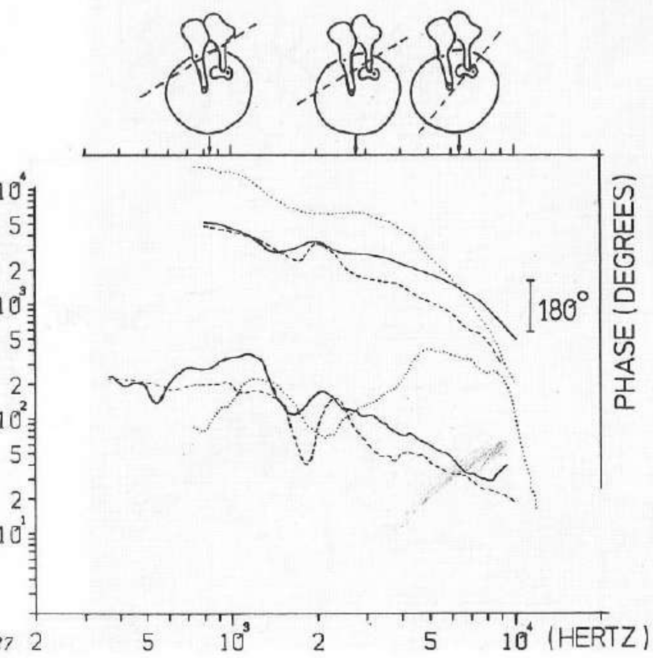

fig. 27

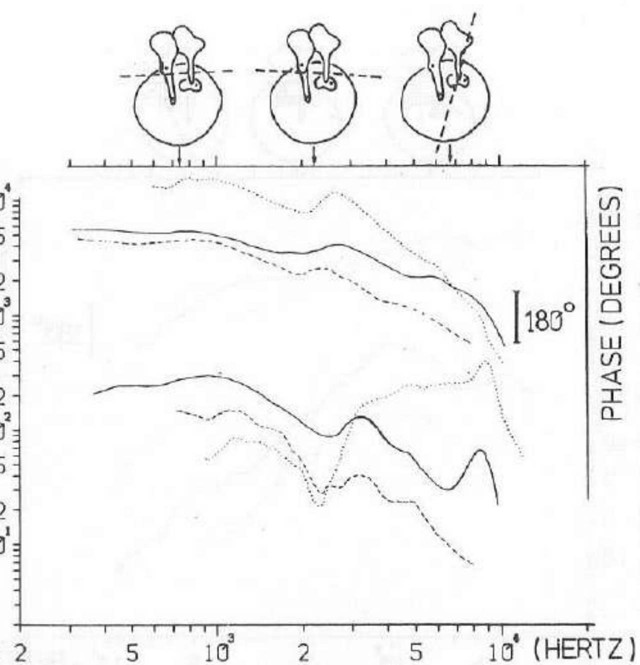

fig. 28

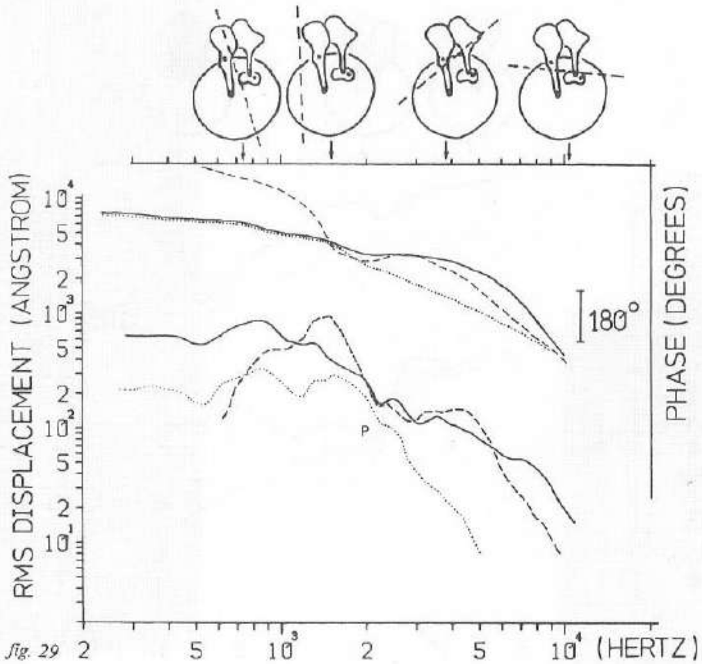

fig. 29

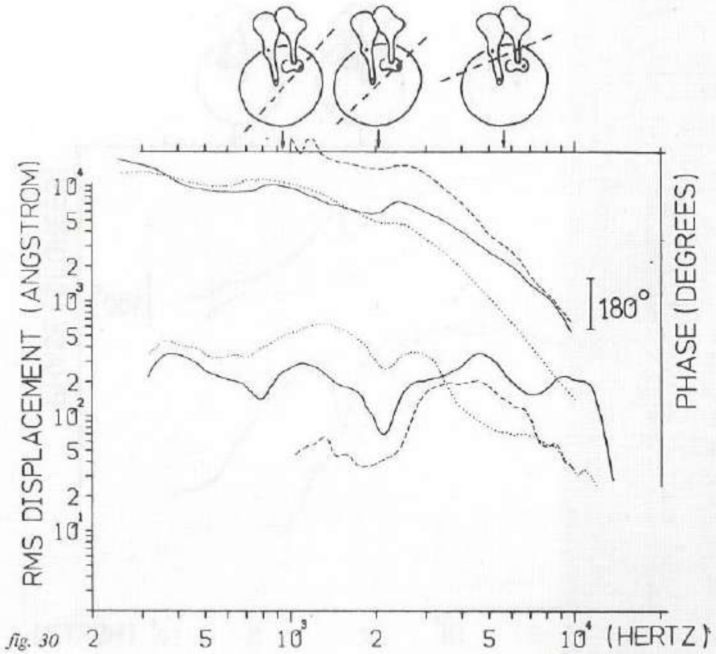

fig. 30

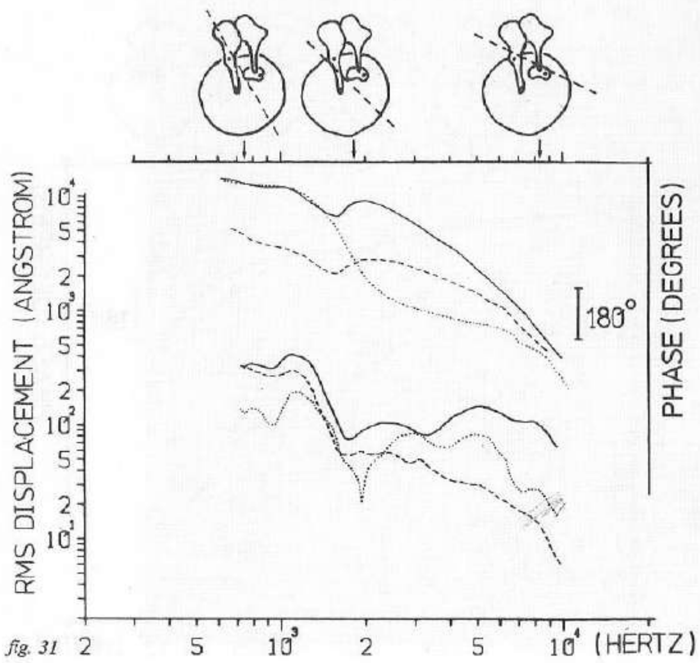

fig. 31

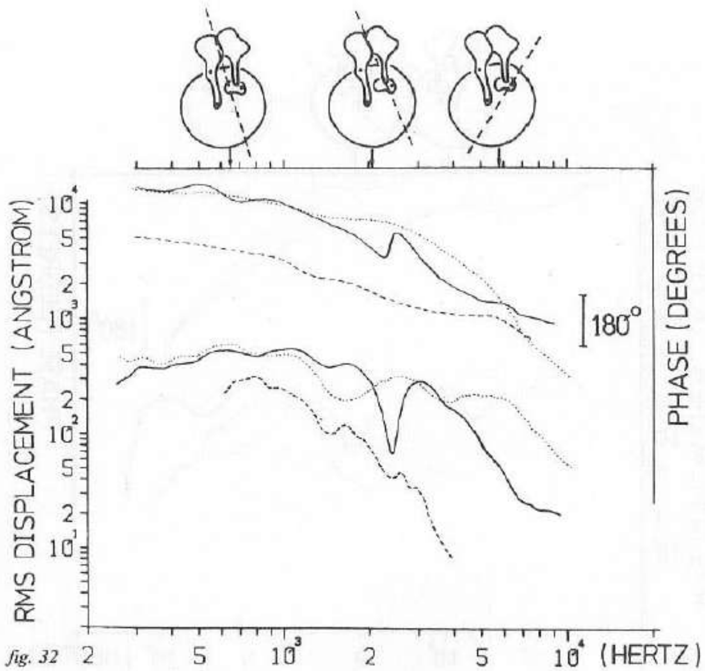

fig. 32

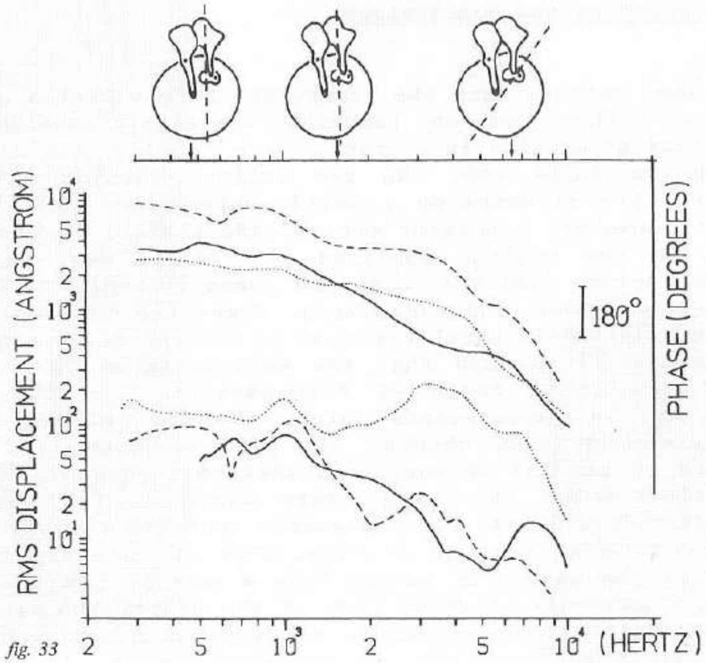

fig. 33

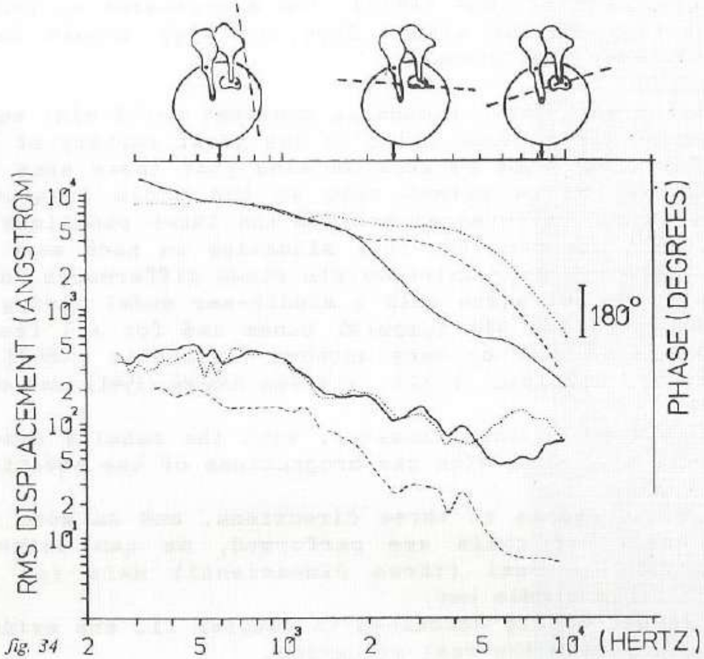

fig. 34

VI.3 Discussion and conclusions

It has been assumed that the ossicular chain vibrates as a rigid body, i.e. without internal friction. One should consider whether or not this assumption is correct.
There is no doubt that the two malleus positions (umbo and pr.brevis) are situated on a solid, unbendable bone. The third position, however, (anterior crus of the stapes) is possibly not related to the malleus position in a rigid way, because two ossicular joints (malleus-incus and incus-stapes) are interposed between the malleus and the stapes. These are the two locations in the middle ear in which friction is theoretically possible.
It is generally assumed that the malleus-incus joint is rigid within the linear range of stimulation. (see chapter II). Concerning the incus-stapes joint, the few references in the literature (see also chapter II) give contradictory results. Therefore it may not be concluded that this joint is rigid like the malleus-incus joint. If there would be friction in the incudo-stapedial joint, it is possible that the stapes is able to vibrate around an axis of its own. This can be very important, because if the stapes is moving like a piston in a cylinder, it makes no difference on which part of the stapes the amplitude is measured. Only in that specific situation are all parts of the stapes moving approximately in the same manner. If there is a rotational movement, as assumed by von Békésy (1936), Kobrak (1948, 1959) and Kirikae (1960), the measurement at the anterior crus position of the stapes does not give enough information about its total displacement.

The division into three groups is somewhat artificial but has the advantage of giving some order to the great variety of axes that can be found. It must be kept in mind that these axes have been calculated at a few points only in the whole frequency range where the phase differences between the three positions were 0°, 180° or 360°. However, the real situation is much more complex, because there are many intermediate phase differences in between. Our results do not agree with a middle-ear model having the same rotational axis for all temporal bones and for all frequencies, as described earlier by many authors (Helmholtz (1868), Dahmann (1929, 1930), Stuhlman (1937), and Von Békésy (1941), see chapter II).
We have to keep in mind, however, that the results described in this thesis only deal with the projections of the rotational axes onto one plane.
Only if measurements in three directions, and on more positions on the ossicular chain are performed, we can determine the position of the real (three dimensional) axis (or axes) of rotation of the middle ear.
The middle-ear models described in chapter II, are evidently too simple to describe the real situation.

CHAPTER VII

GENERAL DISCUSSION AND CONCLUSIONS

This research work is originally undertaken in order to improve the results of reconstructive middle-ear surgery. A fundamental prerequisite for surgical success is an accurate knowledge of the anatomy of the middle ear. Study of the middle-ear apparatus began in the last century, and principally involved a search for an understanding of its typical anatomical structure. At first attempts were made to connect the anatomical findings with the functioning of the middle ear, raising questions as to what exactly were the various functions of the apparatus, and how essential every individual part of the middle ear was for the functioning of the whole. Study of the comparative anatomy in various animal species provided insight into the various types of middle ears, and illuminated many of the connections between structure and function. An instance of this was the study by Johnstone and Taylor (1971) (see chapter II) comparing the "columella ear" with the much more complicated human ear. They concluded that the human middle ear offered major advantages at the highest frequencies. (This did not contradict the surgical results obtained with the columella reconstruction, only because those results were expressed in the Fletcher index which is an average over 500, 1000, and 2000 Hz.
This thesis investigates the transfer of sound through the middle ear. Chapter II describes how researchers have brought us to our present understanding of the transfer function. It has become obvious that much of this knowledge was derived from measurements which frequently included intrusive artifacts and which often were based upon unproven assumptions.
In our own study we found that the transfer characteristics of the middle ear, when based on mean displacement values at umbo and stapes (as described in chapter V), gave the impression of a constant transfer ratio of about 2.5; whereas the measurements of individual temporal bones did not show this constant ratio. Such a varying ratio was neither described nor explained in the literature. We have suggested that the cause of this varying ratio could lie in a displacement loss at the incudo-stapedial joint, or in differing positions for the middle-ear rotational axis which can also occur in combination. A change of the rotational axis would cause a change in lever function, resulting in a different transfer ratio.
The lever function of the middle ear is based on the presence of a rotational axis, the position of which was previously assumed to be rigid, and was established with measurements outside the

linear range of the middle ear or performed with intolerable artifacts.
Gundersen and Høgmoen (1976) were the first to describe a rotational axis that changed with frequency and not with a change in the applied sound pressure. This changing axis is confirmed by the measurements described in this thesis. It was found too that the position of the rotational axis depends on frequency but in contrast to the findings of Gundersen and Høgmoen this dependency also varies with the individual temporal bone. Because the temporal bones were constantly stimulated with 80 dB SPL, the possible influence of a change in sound pressure on the position of the rotational axis was not determined.
The results of our calculation of the projection of the rotational axis allow a division into three groups, depending on the relative phase of the vibrations of the three positions in the low-frequency region. It must be stated, however, that these results do not suggest a uniform pattern for the change in the position of the rotational axis over a large frequency range.
More will be known about both transfer characteristics and the rotational axis (or axes) when more temporal bones have been measured and measured in more directions, and when in vivo measurements are done.
By this point the knowledge about the position of the rotational axis of the cadaver-middle ear should not influence reconstructive middle-ear surgery, especially the design of a total artificial middle ear.

HOOFDSTUK VIII

ALGEMENE DISCUSSIE, CONCLUSIES EN SAMENVATTING

Dit onderzoek had oorspronkelijk tot doel om de resultaten van de reconstructieve middenoor chirurgie te verbeteren.
Een belangrijke voorwaarde om een goed chirurgisch resultaat te bereiken is een nauwkeurige kennis van de anatomie van het middenoor (zie hoofdstuk I). De studie naar het middenoorsysteem begon in de vorige eeuw en gaf een beter inzicht in de anatomie. Aanvankelijk werd geprobeerd om de anatomische bevindingen te koppelen aan het functioneren van het middenoor, hetgeen vragen opwierp naar het functioneren van het systeem in zijn geheel en naar de functie van de verschillende onderdelen. Het bestuderen van de vergelijkende anatomie gaf meer inzicht in de variatie in middenoren bij verschillende diersoorten en gaf aanleiding tot het vermoeden van een samenhang tussen structuur en functie. Een voorbeeld hiervan was de studie van Johnstone en Taylor (1971, zie hoofdstuk II) waarin het "columella oor" vergeleken werd met het meer gecompliceerde menselijke oor. Zij concludeerden dat het menselijke middenoor ten opzichte van het "columella oor" een belangrijk betere overdracht vertoonde in de hoogste frequenties. Dit was niet in tegenspraak met de chirurgische resultaten die verkregen waren met behulp van de columella reconstructie. Deze waren vaak alleen vermeld met een gemiddelde over 500 Hz, 1000 Hz en 2000 Hz.
Dit proefschrift beschrijft de overdracht van geluid door het middenoor. In hoofdstuk II wordt vermeld hoe de ontwikkeling is geweest tot onze huidige kennis van deze overdrachtsfunctie. Vermeld is dat veel van deze kennis werd afgeleid uit metingen waarbij het verstoren van de anatomie vaak tot artefacten leidde en dat deze kennis vaak gegrond was op niet bewezen veronderstellingen. De meetopstelling met de SQUID-magnetometer, zoals beschreven in hoofdstuk III, biedt gegevens over amplitude en fase van verschillende posities in het middenoor. De in dit onderzoek beschreven posities waren het uiteinde van de hamersteel (umbo), een positie halverwege de hamer (processus brevis), en het voorste pootje van de stijgbeugel.
In hoofdstuk IV worden de beperkingen en problemen van de meetopstelling beschreven.
In hoofdstuk V wordt beschreven dat de overdrachtskarakteristieken van het middenoor, gebaseerd op de gemiddelde verplaatsing van umbo en stapes over een breed frequentie gebied de indruk gaven van een constante verplaatsingsverhouding van ongeveer 2,5 terwijl de gemeten verplaatsing van de individuele rotsbeenderen deze constante verhouding niet lieten zien. Een dergelijke variërende verhouding afhankelijk van de frequentie, is noch beschreven, noch verklaard in de literatuur. Wel wordt hierin

gevonden dat de reden voor deze veranderende verhouding kan liggen in een verlies in het incus-stapes gewricht of in wisselende posities van de rotatieas van het middenoor. Een verandering van de rotatieas zou dan een verandering van de hefboom functie geven, resulterend in een verschillende verplaatsingsverhouding.
De hefboomfunctie van het middenoor is gebaseerd op de aanwezigheid van een rotatieas waarvan men aanvankelijk aannam dat de positie vast lag. Echter deze positie van de rotatieas was bepaald d.m.v. metingen waarbij gestimuleerd werd buiten het lineaire gebied van het middenoor of waarbij niet toelaatbare artefacten noodzakelijkerwijs optraden.
Gundersen en Høgmoen (1976) beschreven als eersten een rotatieas waarvan de positie wisselde met een veranderende frequentie en niet met een verandering in de aangeboden geluidsdruk. Deze veranderende as wordt bevestigd door de metingen beschreven in dit proefschrift (zie hoofdstuk VI). Evenals Gundersen en Høgmoen vonden we dat de positie van de rotatieas afhankelijk was van de frequentie maar in tegenstelling tot hun bevindingen varieerde deze afhankelijkheid ook per individueel rotsbeen. Omdat de rotsbeenderen constant gestimuleerd werden met een geluidsdruk van 80 dB SPL werd de mogelijke invloed van een verandering in de geluidsdruk op de positie van de rotatieas niet bepaald.
De resultaten van onze berekening van de projectie van de rotatieas laten zich indelen in drie groepen afhankelijk van de relatieve fase van de uitwijkingen van de drie middenoor posities in het laag-frequente gebied. Het is echter van belang om te vermelden dat deze resultaten geen uniform patroon opleveren voor de verandering van de positie van de rotatieas over een breed frequentiegebied. Indien meer rotsbeenderen gemeten worden en vooral in meer richtingen en van meer middenoor-posities en indien in vivo metingen worden verricht, is het mogelijk om meer te weten over zowel de overdrachtskarakteristieken als de rotatieas over een breed frequentie gebied.
Op dit moment mag de kennis over de ligging van de rotatieas van het middenoor zoals die verkregen is uit de literatuur en uit onze metingen, niet de reconstuctieve middenoorchirurgie beïnvloeden vooral als dit betrekking heeft op het ontwerp van een totaal kunstmiddenoor.

APPENDIX

As Onchi (1961) has shown in a lumped electrical model of the middle ear, the impedance Z, measured at the tympanic membrane can be written as (see his formula 1 and his figs.3 and 4)

$$Z = R_T + \frac{S_z^2 \cos\theta}{w^2 |Z_H|} + \frac{S_M^2 \cos\beta}{w^2 |Z_A|} + j\left(w M_T - \frac{S_{TM}}{w} - \frac{S_z^2 \sin\theta}{w^2 |Z_H|} - \frac{S_M^2 \sin\beta}{w^2 |Z_A|} \right)$$

in which R, S and M stand for resistance, stiffness and mass respectively. T = tympanic membrane. M = middle-ear cavity. H = handle of malleus. S_z = stiffness between malleus handle and middle zone of the tympanic membrane. θ and β are constants. j = $\sqrt{-1}$. $|Z_H|$ and $|Z_A|$ are independent of M_T, so only the first imaginary term is dependent on M_T.

In this lumped model, fixing a magnet to the membrane leads to an increase of M_T only. Inspection of the formula given above easily shows that for large w, i.e.

$$w M_T > \frac{S_{TM}}{w} + \frac{S_z^2 \sin\theta}{w^2 |Z_H|} + \frac{S_M^2 \sin\beta}{w^2 |Z_A|}$$

$|Z|$ increases with M_T.

For low frequencies, when the imaginary part is negative, $|Z|$ decreases if M_T increases.
As $|Z|$ is inversely proportional to w d (constant sound pressure at the eardrum, d = displacement), these relationships imply that for low w the vibratory displacements of the tympanic membrane increase when magnet mass is added, but decrease in the high-frequency region.

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STELLINGEN

I

De positie van de rotatieas van de gehoorbeenketen is niet van belang voor de geluidsoverdracht van het middenoor.

II

Bij de bestudering van de mechanica van het middenoor dient in drie richtingen gemeten te worden, met het intact laten van middenoor en cochlea.

III

De uitspraak van Leukippos, grondlegger van het belangrijkste natuurfilosofische stelsel in de antieke oudheid: "Geen ding ontstaat doelloos, maar alles uit zin en noodzakelijkheid", is niet van toepassing op ieder onderdeel van het middenoor.

IV

Bij maligne tumoren, gelokaliseerd tegen het ethmoiddak of de lamina cribrosa, dient als onderdeel van de operatie de mogelijkheid van resectie van de aangrenzende schedelbasis overwogen te worden.

V

Neuspoliepen zijn niet de oorzaak maar het gevolg van een sinusitis maxillaris chronica.

VI

Gezien de embryologische en postnatale ontwikkeling, het functioneren en de eventuele therapeutische benadering dient de sinus maxillaris als de grootste "ethmoid"cel beschouwd te worden.

VII

Medicamenten die de binnenoordoorbloeding moeten verbeteren, zijn pas werkzaam indien ze dezelfde invloed hebben op de cerebrale doorbloeding.

VIII

Het grote tekort aan donororganen zal de ontwikkeling van kunststof implantaten bevorderen.

IX

Het klinisch onderzoek naar de werking van chemotherapeutica in de oncologie wordt belemmerd doordat vaak te snel van chemotherapeuticum wordt gewisseld.

X

Bij de beoordeling van wetenschappelijk onderzoek dienen maatschappelijke en ethische aspecten een belangrijke rol te spelen.

XI

Bij de geïntubeerde patiënt dient de opgeblazen cuff altijd distaal van het cricoid te liggen.

XII

Indien men het gebruik van taal als communicatiemiddel ziet als een belangrijk onderscheid tussen mensen en dieren, kan men zich afvragen of politici tot de eerste groep mogen worden gerekend.

XIII

The freedom of the subjective person to do as he pleases is overruled by the freedom of the responsible person to act as he must. (Michael Polanyi, in "Personal Knowledge").

C.J. Bronkman — Leiden, 22 okt. 1986.