UNIVERSITY OF SOUTHAMPTON

institute of sound and vibration research

THE EFFECT OF CHANGES IN
CEREBROSPINAL FLUID PRESSURE
ON THE LABYRINTH IN TERMS OF
TYMPANIC MEMBRANE DISPLACEMENT

TECHNICAL REPORT NO. 135
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ABSTRACT

The objective of this study was to investigate the effects of
changes in cochlear perilymphatic fluid pressure on the volume
displacement of the tympanic membrane during acoustically
induced reflex contractions of the stapedius muscle. These
changes in perilymphatic pressure were induced by changing the
body position of normal human subjects and thus varying the
cerebrospinal fluid pressure at the head. The mechanisms by
which changes in body posture affect cochlear fluid pressure have
been investigated by a number of workers and this literature is
also reviewed.

An experiment was carried out on 24 normal subjects in which the
volume displacements of the tympanic membrane during stapedius
muscle contraction were measured in three body positions at
regular intervals over a 20-minutes period and compared to those
measured in the sitting position.

The minute displacements of the tympanic membrane were recorded
using computer-controlled instrumentation specially designed for
the purpose. This measurement system has been developed for a
number of clinical purposes, one of which is to investigate
endolymphatic hydrops in patients with Meniere's Disease. A
secondary purpose of the experiment was thus to evaluate the
sensitivity of the measurement system in terms of these very
small postural pressure changes, and to provide additional
evidence that the direction of tympanic membrane displacement and
its relationship with stimulus intensity are dependent upon
cochlear fluid pressure.

The experimental results show that changes in body position from sitting upright to 30°, 60° and 90° (i.e. recumbent) positions produced significant changes in the reflex-induced tympanic membrane displacement. These changes occurred mainly in the first 5 minutes following the change in posture, although a continuing trend could be discerned over the whole 20 minute measurement period for each position. These findings confirm the previous suggestion that the cerebrospinal fluid communicates directly with the intracochlear fluids in the majority of subjects, probably via the cochlear aqueduct. However, in a minority (12%) of experimental subjects no correlation between body posture and tympanic membrane displacement could be found, and in these cases it is likely that the cochlear aqueduct is not patent.

The experimental findings also showed that the tympanic membrane displacement measurement system can detect intracochlear fluid pressure changes of the order of 30 mm saline in all subjects, and in those exhibiting an inward tympanic membrane displacement this pressure sensitivity improved to 15 mm saline. This pressure change corresponds to a tympanic membrane volume displacement of the order of 3×10^{-8} l or a lateral displacement of the stapes footplate of the order of 1×10^{-6} m.

It is this latter inward type of membrane displacement configuration that is common in patients with Meniere's Syndrome. Thus the measurement system would seem well suited to the investigation of the chronological variations in hydrops that occur in this episodic disorder, and as an aid to its diagnosis.

ACKNOWLEDGEMENTS

CONTENTS

INTRODUCTION

A better understanding of the hydrostatic properties of the
fluids in the inner ear, and their interdependence and
relationship with cerebrospinal fluid (CSF) properties is
essential to our understanding of both normal and pathological
cochlear function. In particular abnormal labyrinthine fluid
pressures, such as associated with Meniere's Syndrome, have been
shown to have a detrimental and sometimes catastrophic effect on
auditory and vestibular functions. Reasons for this are not
conclusively established but mechanical deformation of the
sensory elements, mixing of the labyrinthine fluids via ruptures
in the cochlear membranes, or reduction of the cochlear blood
flow and anoxia are attributing factors. Although inner ear
function is undoubtably linked to the static pressure of the
cochlear fluids, the perilymph and endolymph, until recently very
little progress has been made towards non-invasive means of
detecting abnormalities in these fluids.

Over the past decade, techniques have been developed which
accurately measure movement of the tympanic membrane (TM), and in
particular TM movement induced by the acoustic reflex contraction
of the stapedial muscle. These techniques may be used to gauge
the state of the cochlear perilymphatic fluid pressure because
changes in this pressure produce a small but measurable variation
in the dynamic characteristics of the ossicles and hence the
tympanic membrane. It is the principal objective of the current
research to employ a technique which measures tympanic membrane
displacement (TMD) to evaluate labyrinthine fluid pressure under
various experimental conditions, and thereby increase our
understanding of its normal and abnormal properties.

The inner ear fluids maintain homeostasis by a complex variety of
mechanisms including various ionic, osmotic and metabolic
processes and by mechanical pressure transfer across flexible
boundaries. One factor central to an understanding of these
processes is the cochlear aqueduct, which runs from the scala
tympani into the subarachnoid space. If this aqueduct is fully
patent (open) then the perilymphatic hydrostatic pressure will
directly reflect that of the CSF, and the comparatively large
pressure fluctuations of this fluid system (Davson, 1967). Human
histopathological studies suggest that the patency of this
aqueduct is extremely variable between ears, and is also probably
age dependent.

It is proposed that the state of cochlear aqueduct patency may be found by producing a known change in the CSF pressure and comparing this with the resulting perilymphatic pressure change. This latter parameter is measured in terms of TMD using instrumentation specially developed for the purpose. Changes in CSF pressure are induced by changing the posture of experimental subjects.

Presented in this report is a review of the factors affecting intracochlear fluid pressure and their relevance to certain labyrinthine pathologies. The mechanisms by which raised intracochlear fluid pressure influences the displacement configuration of the TM during stapedial contraction are then reviewed. An experiment is then described in the succeeding chapters in which body position is used to change the CSF pressure in a controlled manner, and the effect of this on the volume displacement of the TM during stapedial contraction is investigated.

CHAPTER 2

A REVIEW OF FACTORS INFLUENCING LABYRINTHINE FLUID
PRESSURE

2.1   Anatomy of the Labyrinthine Fluid System

The hearing and balance organs make up the labyrinth, which in
man consists of the cochlea and the utricle, saccule and semi-
circular canals.   All are contained deep within the temporal
bone in the skull.

There are two distinct types of fluid in the labyrinthine
system: perilymph and endolymph.   Both are very similar in
composition in terms of the amount of proteins, carbohydrates and
sugars present but they differ in the relative concentrations of
sodium and potassium ions. The ionic concentration in endolymph
is high in potassium and low in sodium, whilst the reverse is
true of the perilymph.

The semi-circular canals and the utricle and saccule, which make
up the vestibular (balance) system, are filled with endolymph,
as illustrated in figure 2.1.   The cochlea is divided into three
compartments: the scala tympani and the scala vestibuli contain
perilymph; whereas the middle vessel, the scala media, contains
endolymph and is connected to the saccule by the canalis
reuniens. The scala vestibuli opens onto the middle ear (ME)
through the oval window, though it is sealed by the stapes
footplate and anular ligament.   The scala tympani opens onto the
ME through the round window but again this is sealed, in this
case by a membrane.

These labyrinthine fluids cannot be considered to be contained
within an intact cavity, since there are many passages through
the temporal bone. The largest passage is called the internal
auditory meatus, and this runs from the base of the modiolis
(around which the cochlea is coiled) to an opening in the
subarachnoid space.   There are also numerous small perivascular
and perineural channels through the temporal bone. Of particular
interest are two complex ducts: one associated with the
perilymph and the other with the endolymph.

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Superior Canal — Endolymphatic Sac

Common Crus — Endolymphatic Duct — Saccula

Lateral Canal — Cupular Caecum — Cochlear Duct — Vestibular Scala — Tympanic Scala — Ductus Reuniens

Utricle

Posterior Canal — Round Window — Vestibular Caecum — Middle Ear — Cochlea Aqueduct
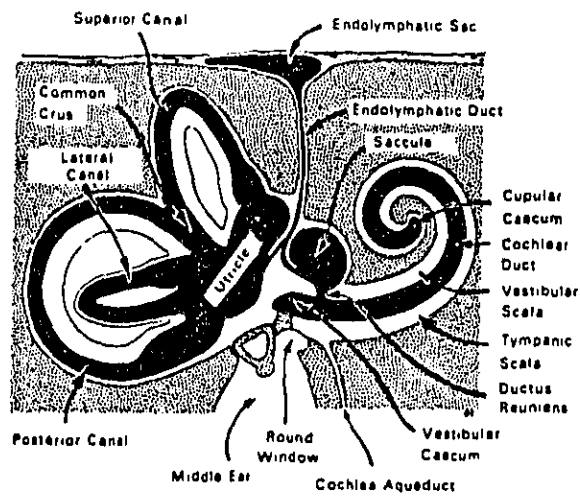
FIG. 2.1   SCHEMATIC DRAWING SHOWING THE GENERAL
CONFIGURATION AND RELATIONSHIP OF THE
ENDOLYMPHATIC AND PERILYMPHATIC SYSTEMS.
From   Schuknecht (1974)

The first, extending from the basal turn of the scala tympani near the round window, is a bony channel through the wall of the cochlea called the cochlear aqueduct, which connects with the subarachnoid space. Within this channel is a loose network of connective tissue continuous with the arachnoid membrane, which extends into the scala tympani onto the round window. This membranous tube is called the periotic duct. For convenience the membranous and bony channels are normally collectively referred to as the cochlear aqueduct.

The second, a long narrow channel known as the vestibular aqueduct, runs through the temporal bone from the saccule to the subarachnoid space. Within the connective tissue of the vestibular aqueduct there is the endolymphatic duct which connects the bulk of the endolymph with the endolymphatic sac. From the histological viewpoint the endolympatic sac consists of three portions: the proximal, middle and distal.

The microscopic differences between these segments of the sac have been thoroughly studied and give the impression of a system with a lively fluid transport and phagocytotic function. Lundquist (1965) indicated that the proximal and distal portions contain low cubic cells, whereas the middle rugose part consist of folds of dark and light cells. The light cells show numerous microvilli and pinocytotic vesicles at the surface towards the endolymphatic space, and at their base have ample indentation of the cell membrane which allows a large active fluid exchange. The dark cells of this portion have a phagocytotic function. Kimura et al (1980) show that the epithelium of the proximal and distal portions of the endolymphatic sac, as well as that of the duct, provide a fluid absorption function. Furthermore, this region is surrounded by an extensive vascular bed, with capillaries which show numerous micropores in their walls. Similar capillary structures were first found in the kidney where they have been related to a particularly active fluid transport system (Rhodin, 1962).

2.1.1 Origins of the labyrinthine fluids

The exact sites of origin of the perilymph and endolymph are still to be determined. Investigations on the site of origin of the perilymph were undertaken by Kley (1951) who injected fluorescent material intravenously and found that it entered the perilymph even though the cochlear aqueduct was blocked. These experiments seem to suggest that perilymph is formed in the perilymph spaces, most probably by transduction from capilliaries.

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Endolymph could also be formed directly by transduction in the endolymphatic space, the most likely source for this being the stria vascularis. Guild (1927) found that a solution of potassium ferrocyanide and iron ammonium citrate injected into the scala media of living guinea pigs often found its way into the endolymphatic sac. From this he concluded that the flow of endolymph is from the stria vascularis through the scala media and canalis reuniens to the sacculi, endolymphatic duct and sac. Alternatively Nftalin (1961) suggested that it could be formed by diffusion through the membranes separating the endolymph and perilymph. This was first suggested by Nftalin as part of a theory of labyrinthine fluid circulation. He proposed that it is formed in the perilymph spaces and then diffuses through Reissners Membrane. Subsequently it is resorbed in the stria vascularis on the outside wall of the scala media. However the earlier view of Guild (1927) has since been supported by Kimura and Shuknecht (1965) in animal experiments in which the endolymphatic sac was blocked, thereby producing endolymphatic hydrops in each case.

2.1.2 Labyrinthine fluid pressures

One of the first measurements of normal endolymphatic and perilymphatic fluid pressure was made by Weille et al (1961) on guinea pigs. They found higher pressure on average in the perilymph than in the endolymph, although they did not measure these pressures simultaneously.

Similarly Martinez (1968) found that the perilymphatic and venous pressures were equal but the endolymphatic pressure was less than the perilymphatic pressure by 14 mm saline.

Due to the physical size of the cochlea and the complexities of making pressure taps into the labyrinthine fluids, there is a considerable degree of difficulty involved in making accurate fluid pressure measurements. Beentjes (1972) claimed to have refined earlier methods and measured the variations in endolymph and perilymph fluid pressures in cats due to cardiac and respiratory variations and found them to be equal, as were the steady state endolymph and perilymph pressures. He thought that the pressure change was transmitted to the endolymph via Reissner's membrane rather than through the vestibular aqueduct.

2.1.3 Patency of the cochlear and vestibular aqueducts

A principal role for the cochlear and vestibular aqueducts is the maintenance of fluid pressure balance between the perilymph, endolymph and CSF. Since the labyrinth effectively forms a sealed cavity it only requires the minutest flow of CSF into or out of the perilymphatic space to maintain pressure balance. Anson et al (1964) examined the anatomy and histology of the cochlear and vestibular aqueducts and concluded that they were well suited to this function.

In the lower animals such as a the guinea pig and cat the lumen of the cochlear aqueduct is relatively wide. Moscovitch et al (1973) measured the mid-course diameter of the cochlear aqueduct of one guinea pig as 240×10^{-6}m, which is wide enough to allow copious bulk flow of the CSF if for any reason perilymph was withdrawn from the system. Experiments using ink particles in guinea pigs (Arning 1951) and blue dye in rabbits (Altmann and Waltner 1950) and cats (Shuknect and Seifi 1963) have all shown that particulate matter can pass through this aqueduct.

In man the cochlear and vestibular aqueducts are both narrower in general and are coated with more connective tissue. Anson et al (1963) measured the calibres of the cochlear and vestibular aqueducts in man as 90 and 380 $\times 10^{-6}$m respectively and concluded that they were not normally patent. However this is not always the case. Schuknecht and Seifi (1963) showed that the human cochlear aqueduct varies in size and, in fact, may be very wide without any apparent detriment to the cochlea.

Wlodyka (1978) studied the cochlear aqueduct patency in 250 temporal bones from human cadavers. He found that although the aqueduct is patent in the foetal stage and remains patent in 82% of ears in the age range of 0 to 39 years, only 20 to 30% of aqueducts are still patent by the age of 60 years. He concluded that the disappearance of cochlear aqueduct patency is a progressive phenomenom reflecting the biological process of aging.

The effect of non-patency of the vestibular and cochlear aqueducts on the pathophysiology of the inner ear has been investigated. Kimura and Shuknecht (1965) were able to produce endolymphatic hydrops (abnormal pressure) and bulging of Reissner's Membrane in the scale media after obliteration of the endolymphatic duct in guinea pigs. It has thus been proposed that congenital or acquired abnormalities of the endolymphatic duct and sac cause the hydrops, with consequent interference with the normal functioning of the cochlea and vestibule. However,

experiments have been performed by Lindsay (1947) on monkeys in which the endolymphatic duct was obliterated but no build up of the endolymph was observed.

Experiments have been carried out on animals in which the cochlear aqueduct has been blocked surgically for long periods of time. Beentjes (1972) found that the labyrinthine fluid pressures appeared to be considerably lower in this situation. Kimura et al (1965) however, could find no histological or functional changes in the inner ear.

2.2 The Significance of the Cerebrospinal Fluid

The cerebrospinal fluid occupies two main compartments of the central nervous system. These are the ventricles of the brain and the subarachnoid spaces. The total volume of this fluid in man is given as about 140 ml, of which only 23 ml is in the ventricles. There is however free communication between the CSF spaces throughout the nervous system and, as discussed, in some instances between these and the perilymphatic fluid.

A detailed decription of the CSF is beyond the scope of this report, and a full review of it has been given by Davson (1970). However, because of its chemical similarities with the perilymph, and the anatomical relationships to both labyrinthine fluids, an understanding of the characteristics of the CSF pressure is clearly important to a consideration of the labyrinthine fluid physiology.

2.2.1 Cerebrospinal fluid pressure

Normal CSF pressure measured in the supine position is somewhere in the range 41 mm of saline to 197 mm saline with a mean of 150 mm (Spina-Franca, 1963). The factors affecting this pressure are numerous and have been studied for over half a century, and are thus fairly well understood. These factors can be grouped into the effects of vascular pressures, posture, osmotic blood pressure, and changes in the formation and drainage of CSF.

Considering first the effects of changes in vascular pressure: the CSF pressure itself follows both cardiac and respiratory pressure variations. A cardiac pulse of 20 mm saline and a respiratory variation of 35 mm saline were recorded by Goldensohn et al (1951). Bering (1955) however found a cardiac pulse of 50 mm saline. A rise in averge CSF pressure results in an

increased amplitude of the cardiac and respiratory variation. Goldensohn et al (1951) found average cardiac and respiratory variations of 70 mm and 75 mm saline respectively when the mean fluid pressure was 300 mm, compared with values of 20 mm and 35 mm respectively when the mean fluid pressure was 100 mm. Bering (1955) made measurements of the time course of the cardiac pulse in the cerebral ventricle. When compared with the electrocardiogram it was apparent that the pulse immediately follows systole and is unconnected with the central venous pulse. Dunbar et al (1966) have also confirmed this close relationship between CSF and arterial pressures, as opposed to venous pulses.

According to Freemont-Smith and Merritt (1933), both the mean arterial pressure and small variations in it have very little direct effect on the CSF pressure. Davson (1970) proposed a mechanical model to account for these results, in which the CSF is contained in a rigid walled container through which pass elastic walled arteries and veins. The model predicts that rapid alterations in arterial pressure will produce rapid but highly damped changes in the CSF pressure, although small alterations in arterial pressure will produce no direct effect on the CSF. Alterations in venous pressure will be readily transmitted to the CSF pressure however.

Variations in the gas levels in the blood cause variation in the CSF pressure. Both an excess of carbon dioxide and a deficiency in oxygen cause a rise in systemic arterial blood pressure, which by itself does not affect CSF pressure, together with an increase in the calibre of the cerebral arteries which then directly increases CSF pressure (Wolff and Lennox 1930). These homeostatic mechanisms operate so as to ensure adequate aeration of the brain tissue, hence the dilation of the cerebral arteries. It is due to these homeostatic mechanisms maintaining constant cerebral blood flow that the CSF pressure is remarkably resistant to the effects of drugs (Sokoloff 1959). It is also known that vasodilators cause dilation of the cerebral vasculature and thus raise CSF pressure. Anaesthetics also affect the CSF pressure, mainly due to their effect on respiration which causes short term changes in the gas content of the blood.

According to Riser (1929) very large changes in CSF pressure can be produced by coughing (ca. 175 mm saline) and sneezing (ca. 250 mm saline). Emotional and psychological states also affect CSF pressure significantly. Haug (1932) concluded however that despite these temporary variations, CSF pressure was reproducible from day to day in one subject to within 30 mm saline, provided the pressure was allowed to settle down over a 10 minute period.

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In a similar manner to the endolymph and perilymph, the rates of formation and drainage of CSF are obviously very important in determining the mean CSF pressure. Blocking the outlets of CSF results in large increases in CSF pressure (Bering and Sato, 1963), suggesting that the formation process continues. The rate of formation of CSF is such that it is totally replaced several times a day.

Changes in the osmotic pressure of the blood can also affect CSF pressure. The main cause of this is the formation of urea. Urea usually crosses the blood-brain barrier and is a hyper-tonic solute and so reduces the CSF pressure.

A further major influence on CSF pressure is posture and this will be discussed in detail in section 2.3.1.

2.2.2 Transmission of CSF to labyrinthine fluid pressure

Martinez (1968) reported the CSF pressure in guinea pigs and cats to be greater than the perilymphatic fluid pressure by 14 mm saline. It thus seemed to Martinez that direct communication between the perilymph and the CSF did not exist. Variations in CSF pressure however were transmitted to the perilymph fluid pressure once the differential reached a certain pressure. This pressure difference then remained stable. Changes in venous and arterial pressures were also transmitted to the perilymph but not by the same degree to the endolymph.

This result disagrees with an earlier investigation by Kerth and Allen (1963) who measured the perilymphatic and CSF pressures simultaneously in cats and found them to be equal. During experiments with cats Beentjes (1972) found that the CSF pressure appeared to be 10 mm saline higher than that of the perilymph, but he felt that this may be an artefact due to the use of two measuring systems. So as to investigate the transmission of CSF pressure to the labyrinthine fluid, he produced a large, rapid increase in the CSF pressure by applying abdominal pressure. This caused the CSF pressure to increase by a factor of two to three times and produced a corresponding increase in both the perilymph and endolymph pressures, though over a longer period. This led Beentjes to conclude that, in the cat, all CSF pressure variations are readily transmitted to the perilymph via the cochlear aqueduct.

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More recently Carlborg et al (1980, 1981) have made extensive
investigations into the correlation between perilymph and CSF
pressures in the cat. They found no difference between the mean
perilymph and CSF pressures. Carlborg et al explained this by
claiming that the previous pressure measurements which showed a
difference were not mean values. They also varied the CSF
pressure by various means, such as by altering posture, blood
pressure and blood gas content. They concluded that, however
the CSF pressure change was brought about, it was exactly
reflected in the perilymph pressure with virtually no time lag,
provided the CSF pressure variation was reasonably slow.
However during the cardiac pulse, which produces large and rapid
variations in the CSF pressure, the perilymph pressure variation
was two to three times less than the CSF pressure variation, and
lagged behind it by 0.2 to 0.4 seconds. Carlborg et al
suggested that this was due to the damping introduced by the
cochlear aqueduct. In man however, the cochlear aqueduct is
much smaller in diameter than the cat, which might serve as a
protective mechanism against sudden changes in CSF pressure.

2.3   Postural Effects on Intracranial Fluid Pressure

Postural effects on the intracranial fluid pressure are important
to this research in two respects. Firstly, changes in posture
provide a controllable means by which the CSF pressure in man may
be altered experimentally, and therefore its effect on the
labyrinthine fluid pressure may be investigated. Secondly, as
discussed later in this chapter, under certain pathological
conditions a change in posture can precipitate or exacerbate
attacks of paroxysmal vertigo in man.

2.3.1   Posture and CSF pressure

Conventionally, CSF pressure is described in terms of an
equivalent column of saline solution. In the sitting position,
the pressure of the CSF at the base of the spine will be greater
than the intracranial pressure by an amount equal to the
hydrostatic pressure of a column of saline solution the same
height as the vertical distance between the base of the spine and
the cranium (Loman 1934). The pressure in the cranium might
then be expected to increase when the subject is moved from an
upright sitting position into the recumbent position, by an
amount equal to the hydrostatic pressure of the spinal-
subarachnoid fluid column.

Masserman (1935) monitored the lumbar spinal CSF pressure in various positions. Compared with the pressure in the recumbent position, however, he found that the pressures in the sitting and 30° downwards incline positions were only 40% and 33% respectively of those expected.

Weed and Flexner (1932, 1933) suggested that this discrepancy was due to the walls of the CSF system not being totally enclosed. They proposed an elastic component that allows some transmission of atmospheric pressure to the CSF. Thus, although an increase in CSF pressure can be produced, the full effect of the hydrostatic column pressure in the sitting position is prevented from manifesting itself. This elastic component could either be due to the elasticity of the cervical dura (meninges) or to the changes in venous pressure that accompany postural changes.

The importance to the CSF of venous pressure changes associated with posture was shown by Flexner and Weed. They tilted dogs into the head-down and head-up positions and found that the venous pressure was greater than the CSF pressure. It is thus the tendency of the veins in the lumbar region to empty and those in the head to engorge in the head-down position, and vice versa for the head-up position, that prevents the fluid column from having its maximum theoretical hydrostatic effect.

Thus the CSF pressure that results from different postures seems to be influenced by three factors: the hydrostatic pressure of the fluid column, the transmitted blood pressure and the elastic tension of the meninges.

The postural responses so far described take immediate action. Bedford (1958, 1959) measured the longer-term effect of changes in posture. He maintained dogs in the head-down position and found that the initial rise in pressure in the cisterna magna (cranium) was compensated for, as it returned to normal within 15 to 30 minutes. On then returning the animal to the horizontal position the pressure fell, although over a period of 30 minutes it again returned to its original value. On moving the animal to the head-up position the compensation to normal pressure took place within a few seconds. This rapid compensation to the head-up position could possibly indicate the play of vascular reflexes that keep the fluid pressure within a specific range.

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2.3.2 Posture and labyrinthine fluid pressure

The effect of varying posture on the perilymph pressure in cats
was investigated in some detail by Carlborg et al (1980, 1981).
The results of this work are worth considering in detail as they
are particularly relevant to the present study.   Figure 2.2
shows the resulting pressure changes for various angles of body
inclination.

Their results invariably showed that increasing the inclination
of the body caused an equal and gradual rise in the CSF,
perilymph and the jugular vein pressures without any noticeable
time lag.   The rise in pressure amounted to about 19 mm saline
(0.27 kPa) for each 10° change in body position upto $+30^{\circ}$.   Above
$+30^{\circ}$ the rise was slightly smaller.   Two cats were kept tilted at
$+30^{\circ}$ (head down) for two hours.   After a few minutes both
perilymph and CSF pressures fell gradually, though not to pretilt
levels.   A pressure gradient was also established between the
perilymph and CSF of between 11 and 21 mm saline (0.15-0.30 kPa)
due to the larger fall in perilymphatic pressure.

2.3.3 Posture and hearing

Auditory threshold shifts resulting from changes in posture have
been studied in humans by Miltich (1968) and Macrae (1972).

Miltich found a mean threshold shift at 500 Hz of 1.1 dB when the
subject moved from the upright to supine position, 13.2 dB when
moved from the supine to the inverted position, and 14.7 dB when
moved from the upright to the inverted position.   For the latter
two postural changes, the thresholds improved by 5 dB within 30-
45 seconds of moving to the new position, but then remained
constant thereafter.

Macrae found a threshold change of 8 dB when the subject moved
from the upright to the inverted position.   He also reported
that both the resistive and reactive components of the TM
acoustic impedance were increased on moving from the upright to
the inverted position.   However Macrae felt that this could
only account for about half the threshold shift found.
Additionally the compliance changes induced by reflex
contractions of the ME muscles were reduced on moving from
upright to the inverted position, by 80% for the stapedius muscle
and by 25% for the tensor tympani.   He proposed that this was
due to the increased load on the stapes footplate due to raised
intra-cochlear fluid pressure.
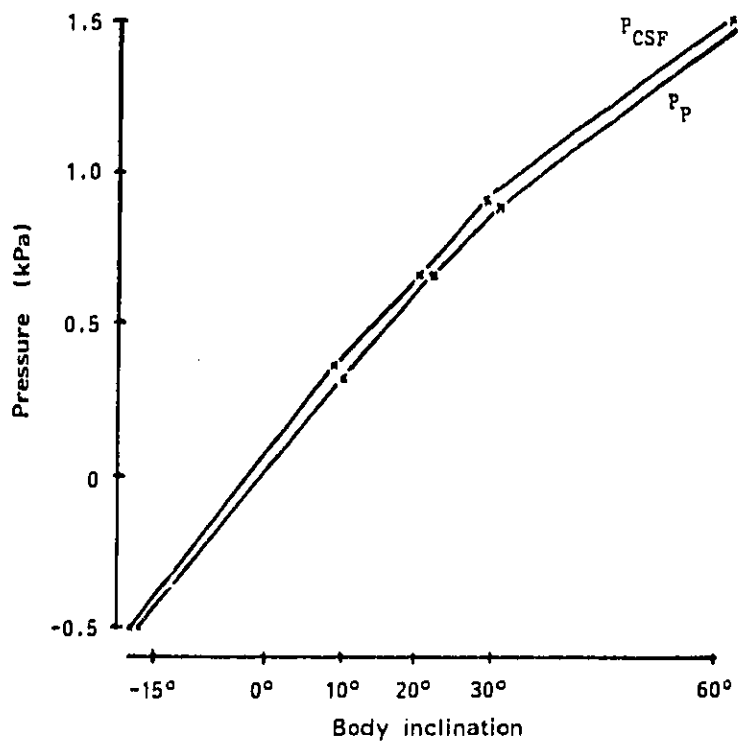
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FIG. 2.2   THE EFFECT OF CHANGES IN BODY POSITION ON
            THE MEAN PERILYMPH FLUID PRESSURE AND
            CEROBROSPINAL FLUID PRESSURE IN 7 CATS.
            From   Carlborg (1981)

The effect of labyrinthine fluid pressure on auditory acuity has also been measured directly by Feldman (1968). He raised the CSF pressure of cats by injecting Ringer's solution into the subdural space of the lumbar spine, and then recorded the cochlear microphonic potential (CMP). For a CSF pressure of 204 mm saline, the CMP near thresholds was reduced by 30 dB at 125 Hz and by 20 dB at 8 kHz. He also plotted input/output functions which showed that, with a stimulus at 110 dB SPL at 250 Hz in the external auditory meatus, the CMP was reduced by 40 dB at a CSF pressure of 204 mm saline.

2.4 Labyrinthine Fluid Pressure Related Pathologies

A number of pathologies with non-specific aetiologies effect the labyrinthine fluid pressures. One of the primary motives for the current investigation is to improve the understanding of the causes of Meniere's Syndrome and Meniere's-like disorders (Marchbanks and Martin, 1984a).

2.4.1 Meniere's disease and meniere's syndrome

In 1861 Prosper Meniere first described the symptoms of a disorder which has become known as 'Meniere's Disease'. Since then the term has often been improperly applied to medical conditions where the patient complains of some sort of dizziness. More recently there have been several attempts to rationalise the description of 'Meniere's Disease' in terms of classes of symptom complexes; for example by the American Committee on Hearing and Equilibrium on Meniere's Disease (Alford, 1972), the Meniere's Disease Research Committee of Japan (Watanabe, 1974), and Pfaltz and Matefi (1981).

Pfaltz and Matefi (1981) suggested the use of the following diagnostic criteria for Meniere's Disease:

1. Spontaneous, repeated attacks of vertigo with vegetative symptoms.
2. Spontaneous nystagmus during an attack,but no nystagmus in the intervals.
3. Unilateral fluctuating hearing loss, increasing during and after an attack, and fluctuating tinnitus in the same ear.
4. Low-frequency hearing loss in the begining of the disease, together with positive recruitment.
5. Within a year after the onset of the disease Meniere's triad of symptoms will be complete.

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Patients suffering from a similar but not identical set of symptoms are said to have 'Atypical Meniere's Disease'. For example cochlear Meniere's Disease is an atypical form where all but the vestibular signs are present. Likewise Vestibular Meniere's Disease occurs where all but the auditory signs are present.

The American Academy (Alford, 1972) suggested a slightly more relaxed set of criteria where the presence of tinnitus is not an essential component. The apparent anomaly here, in that tinnitus is not essential, results from an attempt to identify Meniere's Disease as a clinical entity based on one single causative factor. This causative factor is generally thought to be endolymphatic hydrops resulting from abnormalities of the endolymph supply or absorption processes. Nevertheless, histopathological studies often show no evidence of hydrops in patients sufferring from Meniere's Disease, even when diagnosed on the most conservative criteria (Schuknecht, 1974).

The actual relationship of Meniere's Disease with endolymphatic hydrops was not found until 1938 when Hallpike and Cairns sectioned the temporal bones of two Meniere's patients who had died during operations. They found marked dilation of the endolymphatic spaces in the cochlea and the vestibule. Lindsay (1946) enlarged the number of pathological studies and confirmed this finding. It is still not known what causes this dilation however. It could be produced by over-production of endolymph, by alterations in its composition or by interference with its absorption or drainage.

How endolymphatic hydrops produces the symptoms of Meniere's Disease is also not fully understood. Hydrops could interfere with the microcirculation of the inner ear fluids, or alter the ionic content. It has also been proposed that the pressure build-up causes Reissner's Membrane to rupture, with consequent mixing of endolymph and perilymph. This leads to a subsequent increase in potassium ionic concentration which affects both the auditory and vestibular nerve branches. The latter hypothesis is a plausible explanation which in general provides a single causative factor for Meniere's Disease, as well as its atypical forms (Dohlman, 1983; Kitahara et al., 1984). However, many patient groups within the various categories of Meniere's Disease do not, when studied in detail, have symptoms which agree with this explanation. For example, a fairly common exception is where vertigo follows virtually instantaneously after identifiable precipitating factors, such as postural changes, and insufficient time is available for the proposed mixing of the cochlear fluids.

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Generally speaking a Meniere's-like disorder may be defined in two ways: either specifically in terms of a symptom complex only, or an attempt may be made to identify an underlying cause. Both approaches have severe limitations in the practical sense when it comes to patient management. The former will be limited because the predictive power of any specific symptom complex is fairly minimal on an individual patient basis, due to the wide range of possible pathologies within such a group. The second approach will be limited by the fact that any disorder which is identifiable in the pathophysiological sense, will undoubtably show different symptom complexes on an individual patient basis, due for example to anatomical variation.

In the long-term the second approach is likely to be more benificial, and the current research relates to this in two respects. Firstly, by investigating the underlying causes of these disorders, so that subtle but significant differences in the symptoms may be identified. Secondly, by providing an objective means of measuring abnormalities of cochlear fluid system and pressure, and thus improving the diagnostic sensitivity of the clinical test battery.

2.4.2 Paroxysmal vertigo

The term 'Meniere's Disease' is commonly incorrectly used in cases of Paroxysmal Vertigo, which is assumed to be an idiopathic disorder. For the purpose of studying this disorder, Oosterveld (1983) rather arbitarily defined it as being 'repeated attacks of vertigo, accompanied by vegetative symptoms lasting from 3 minutes up to 24 hours, and existing for a period of 1 year or more'. Specific as it may seem, this definition excludes a significant population of patients where the vertigo last for less than 3 minutes.

Although a duration of 3 minutes for the lower limit appears to be an arbitary choice, it has some significance to the underlying pathophysiology in the present case. For the purpose of current considerations, the existence of a pathological condition whereby a rapid change in CSF pressure causes a concommittant pressure change in only one of the two labyrinths, thus producing vertigo, is an interesting possibility. Such mechanical influences on the vestibular organs will last for less than 3 minutes. It can be hypothesised that this asymmetrical condition may occur under certain circumstances during the expected active maturation stage of the cochlear aqueduct, from normally patent in the early stages of life to sealed in the later stages (Wlodyka, 1978).

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2.5 Concluding Discussion

The effects of changes in the CSF and perilymph pressures still remain speculative, both in the case of normal ears and in Meniere's syndrome. However, a factor of paramount importance is the value of the pressure differential between the endolymph and perilymph fluids. Beentjes (1972) showed that this pressure must be small since, for pressure differentials greater than 10 to 20 mm saline, ruptures of the endolymphatic membrane system can occur.

In cases where the cochlear aqueduct is patent, the perilymphatic pressure will directly reflect changes in the CSF pressure. As already discussed, normal CSF pressure fluctuations often exceed several hundred millimeters saline over periods of a few seconds or less. Therefore the only mechanism for a pressure transfer to the endolymph, such that the critical perilymphatic pressure is not exceeded, is via Reissner's membrane itself. Since the endolymphatic system is effectively sealed, such a change in endolymphatic pressure must be accomodated in the normal ear by a small displacement of Reissner's membrane. Under these circumstances the pressure differential between the two fluids must remain substantially less than 10% of the overall change in the CSF pressure. From mechanical considerations, this pressure differential is equal to the tension of Reissner's membrane.

The same is not true in the case of a cochlear aqueduct that is not patent, and where an abnormal change in the endolymphatic pressure has been brought about by a variation in endolymph production or absorption. Here the endolymphatic hydrops causes Reissner's membrane to be under tension, such that the membrane is less compliant and more susceptible to changes in CSF pressure. Under these circumstances any excess CSF pressure, perhaps caused by changes in posture, will be supported by this membrane, so that ruptures or other damage to it may occur. Clearly in the normal ear the endolymphatic production/absorption process must be fairly critically controlled if excessive dilation or damage to Reissner's membrane is to be avoided.

In the instance of a patent cochlear aqueduct, the TMD technique employed in this research will not detect pressure abnormalities in the endolymph itself. Nevertheless, confirmation of the presence of a patent aqueduct by this technique may prove to be important in predicting a CSF related time-course of a pathology.

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In the case of a sealed cochlear aqueduct, however, the endolymphatic pressure will be transmitted directly to that of the perilymph within the vestibule region and will therefore be measurable with the TMD measurement technique. There are reasons to believe that this case may well be the norm with Meniere's Disease. This is because patients in the age group normally associated with Meniere's Disease demonstrate a tendency for the aqueduct to be sealed (Wlodyka, 1978); and the fact that excessive dilation of Reissner's membrane has been shown to block the helicotrema and scala vestibuli, thereby isolating the scala vestibuli from the scala tympani and cochlear aqueduct (Paparella, 1984). In this latter instance the perilymph may combine with Reissner's membrane to support a greater endolymphatic pressure before rupture than would otherwise be possible.

The presence or otherwise of a patent cochlear aqueduct, measures of perilymphatic pressure, and an understanding of the effect of the CSF on labyrinthine fluid pressure all appear to be important factors governing the progression of labyrinthine-fluid related disorders such as Meniere's Disease.

MODELS OF THE MECHANICS OF STAPES MOTION AND THE EFFECTS OF CHANGES IN INTRACOCHLEAR FLUID PRESSURE

Changes in the hydrostatic pressure of the perilymph produce a small but measurable variation in the dynamics of the ossicles and tympanic membrane. This effect is primarily due to the hydrostatic pressure exerting a force sufficient to influence the resting position of the stapes in the oval window, and consequently the degree of freedom of inward TM motion (Densert et al, 1977; Brask, 1978; Marchbanks, 1980; Marchbanks and Martin, 1983). In the current studies a movement of the TM is induced by contraction of the stapedius muscle in response to acoustic stimulation of the stapedial reflex, and the resulting displacement is measured using the TMD measurement technique (Marchbanks, 1980).

Various models of the effects of raised perilymphatic pressure on the movement of the stapes during stapedial contraction have been reviewed by Tweed (1985) and will be summarised only briefly here.

3.1   An Electromechanical Model

Brask (1978) was the first to model the perilymphatic-pressure/stapes-interaction with an electromechanical analogue of the stapes and oval window which is represented schematically in Figure 3.1.   This mechanical analogue yields the lateral displacement of the head of the stapes, which is the motion transferred to the TM during stapedius muscle contraction.   By varying the elasticities of the posterior and anterior parts of the annular ligament, Brask produced three types of reflex-induced TM displacement configuration.   These configurations are represented in Figure 3.2.   In part (a) the elasticity AA^1 is greater than PP^1 so the stapes hinges round the posterior pole and an outward displacement is produced.   If PP^1 is made more elastic than AA^1, an inward displacement results (part b). Brask also demonstrated a biphasic displacement of the TM, Figure 3.2(c), by initially making AA^1 less elastic than PP^1, but then as the strength of contraction increased the elasticity of PP^1 is reduced so that AA^1 is the more elastic.

Anterior

Elastic
ligament

Elastic
ligament
(variable
stiffness)

Strength and dynamics
of stapedial contraction
variable
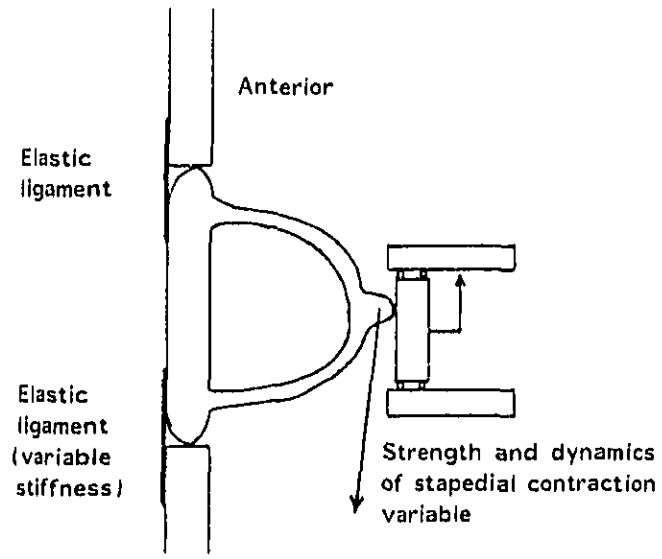
FIG. 3.1   SCHEMATIC REPRESENTATION OF BRASK'S ELECTRO-
MECHANICAL MODEL OF THE STAPES AND OVAL
WINDOW.
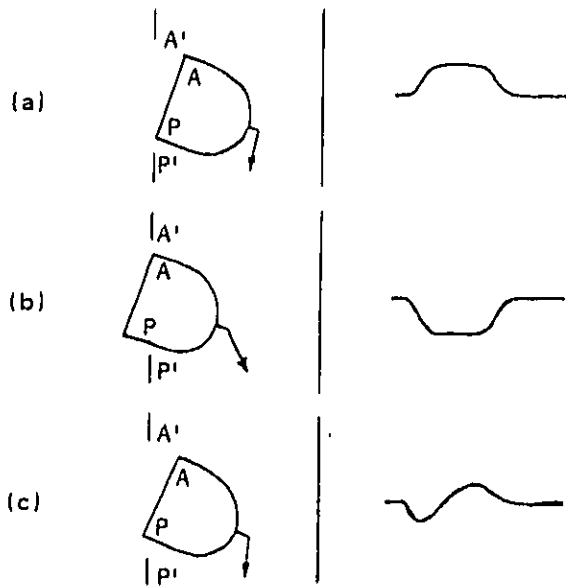
FIG. 3.2   THE POSITIONS OF THE STAPES AFTER A STAPEDIUS
           CONTRACTION AND THE CORRESPONDING ETM
           REFLEX CURVE FIGURATIONS ACCORDING TO BRASK,
           1978. (See text for explanation)
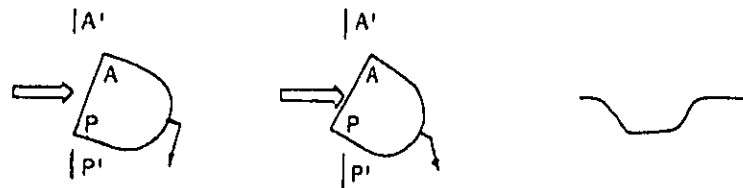
FIG. 3.3   THE POSITIONS OF THE STAPES BEFORE AND AFTER
           A STAPEDIUS CONTRACTION WITH THE CORRESPONDING
            TM REFLEX CURVE CONFIGURATIONS, DURING THE
           CONDITION OF INCREASED PRESSURE ON THE FOOT-
           PLATE FROM THE PERILYMPHATIC FLUID. (Brask,1978)

The effect of an outward force on the stapes footplate, to
represent raised perilymph fluid pressure, is to turn the outward
displacement shown in Figure 3.2(a) into an inward displacement,
Figure 3.2(b), because the elasticity of AA[1] is "used up" before
the full movement is completed.

3.2   Mathematical Models

Marchbanks and Martin (1984a) modelled the stapes mechanics
mathematically. To simplify the situation they constrained the
stapes footplate to move only perpendicular to the plane of the
footplate, and to rotate about an axis in the plane of the
footplate perpendicular to the pull of the stapedius, as shown in
Figure 3.4. The stapes motion was derived by equating the forces
acting on the stapes, namely those due to the posterior and
anterior regions of the annular ligament, the hydrostatic force
applied by the perilymph, and the force applied by the stapedius
muscle tendon. The force applied through the incudo-stapedial
joint was taken into account in the elasticity function for the
oval window obtained in experiments performed on human temporal
bone preparations (Densert et al, 1977; Ivarsson and Pedersen,
1977). Typical values for the footplate cross section and stapes
dimensions were obtained from Schuknecht (1974). A computer
using an iterative procedure was used to simulate the motion of
the head of the stapes for increasing tension within the
stapedial muscle tendon. Allowances were also made for the non-
linear elastic properties of the annular ligament.

The lateral displacement of the head of the stapes that
Marchbanks and Martin (1984a) computed from their model is
plotted against stapedius force for a number of perilymph fluid
pressures in figure 3.5. The model clearly demonstrates that an
increase in perilymphatic fluid pressure produces a more inward-
going reflex-induced TMD configuration. Conversly a decrease in
pressure results in a more outward going displacement.
Furthermore, the model predicts that the amplitude of the reflex
TMD configuration will increase for increasing perilymphatic
pressure.

The stapes footplate mechanics were subsequently modelled in
greater detail by Tweed (1985). The model is shown schematically
in Figure 3.6. The stapes is allowed to move in any manner in the
two-dimensional plane, which approximates to the real situation
very closely.   Using data published by Ivarsson and Pedersen
(1977) and the description of the anatomy by Bruner (1954),
estimates of the elasticities of the posterior and anterior parts
of the annular ligament were made.
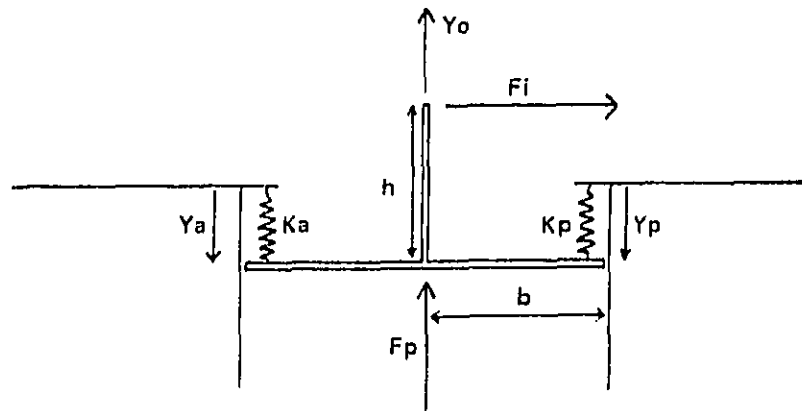
FIG. 3.4   MARCHBANKS' ONE DIMENSIONAL MODEL OF THE MOTION
OF THE HEAD OF THE STAPES DURING STAPEDIAL
CONTRACTION.

Perilymphatic Pressure

A. 0·0 N/m²   B. 118 N/m² (12 mmWg)

C. 294 N/m² (30mmWg)   D. 372N/m² (38mmWg)

E. 441 N/m² (45mmWg)
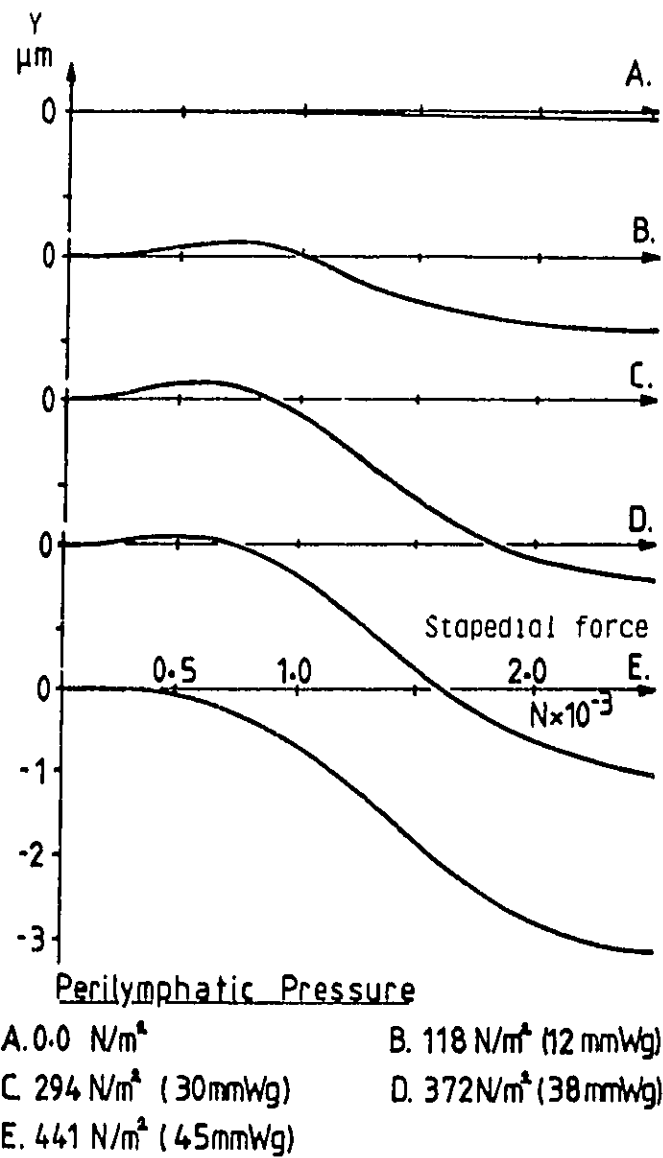
FIG. 3.5   LATERAL LINEAR DISPLACEMENT OF THE HEAD OF
            THE STAPES FOR INCREASING PERILYMPHATIC
            PRESSURE ACCORDING TO MARCHBANKS' ONE –
            DIMENSIONAL MODEL. (Marchbanks and Martin, 1984)
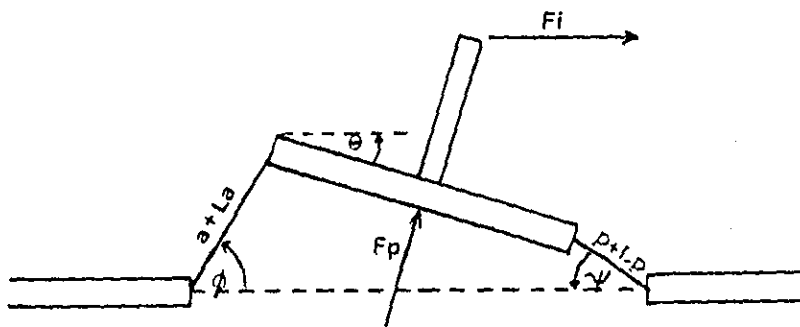
FIG. 3.6   SIMPLIFIED TWO-DIMENSIONAL MODEL OF THE STAPES
AND OVAL WINDOW WITH THE FORCES OF THE STAPEDIUS
MUSCLE, Fi AND THE PERILYMPHATIC FLUID PRESSURE,
Fp ACTING.   (Tweed, 1985)

Using these estimates an outward lateral displacement of the head
of the stapes is predicted for equal pressure on either side of
the footplate.   As the perilymphatic fluid overpressure is
increased the direction of this TMD first becomes biphasic and
then inward,   as   illustrated   in   Figure 3.7.

The model of Tweed (1985) was also used to investigate the effect
of varying the relative thicknesses of the posterior and anterior
regionsof the annular ligament, following normal anatomical
variations.   He found that the influence of the perilymphatic
pressure on the TMD was dependent on the length of the posterior
part of the ligament.   Additionally Tweed demonstrated that a
small posterior ligament thickness reduced the 'inward-goingness'
of the reflex displacement configuration in the presence of high
perilymphatic fluid pressure.   Tweed thus concluded that the
change in the reflex-induced TMD configuration produced by
changing the CSF using body postural maneuvres may be a more
sensitive indicator of raised perilymphatic fluid pressure in
patients with Meniere's type disorders.

3.3   Comparison of Mathematical Models

The mathematical model of Marchbanks and Martin (1984a) and the
refined model of Tweed (1985) both predict that an increase in
perilymphatic pressure will result in a more 'inward-going'
reflex-induced TM displacement.   In general terms, Tweed's model
more accurately predicts the actual stapes mechanics and should
therefore be a more accurate predictor of TM motion for extremes
of perilymphatic pressure.   This is also the case for large
differences in posterior and anterior ligament dimensions and for
greater amplitude of stapes motion, that is for greater stapedius
muscle contraction force.

However, the model does not accurately predict the volume
displacement of the stapes footplate for small changes in
perilymphatic pressure.   Comparison with real data obtained
from human temporal bones (Ivarsson and Pedersen, 1977) shows
that the Tweed model predicts an oval window compliance that is
too great at these near-zero perilymphatic pressure changes.
Consequently the Marchbanks and Martin (1984a) model may be used
to describe the reflex TM motion through the zero pressure
transition region, whereas the Tweed model is only accurate for
pressures greater than nominally 3 mm saline   or less than -3 mm
saline.

20
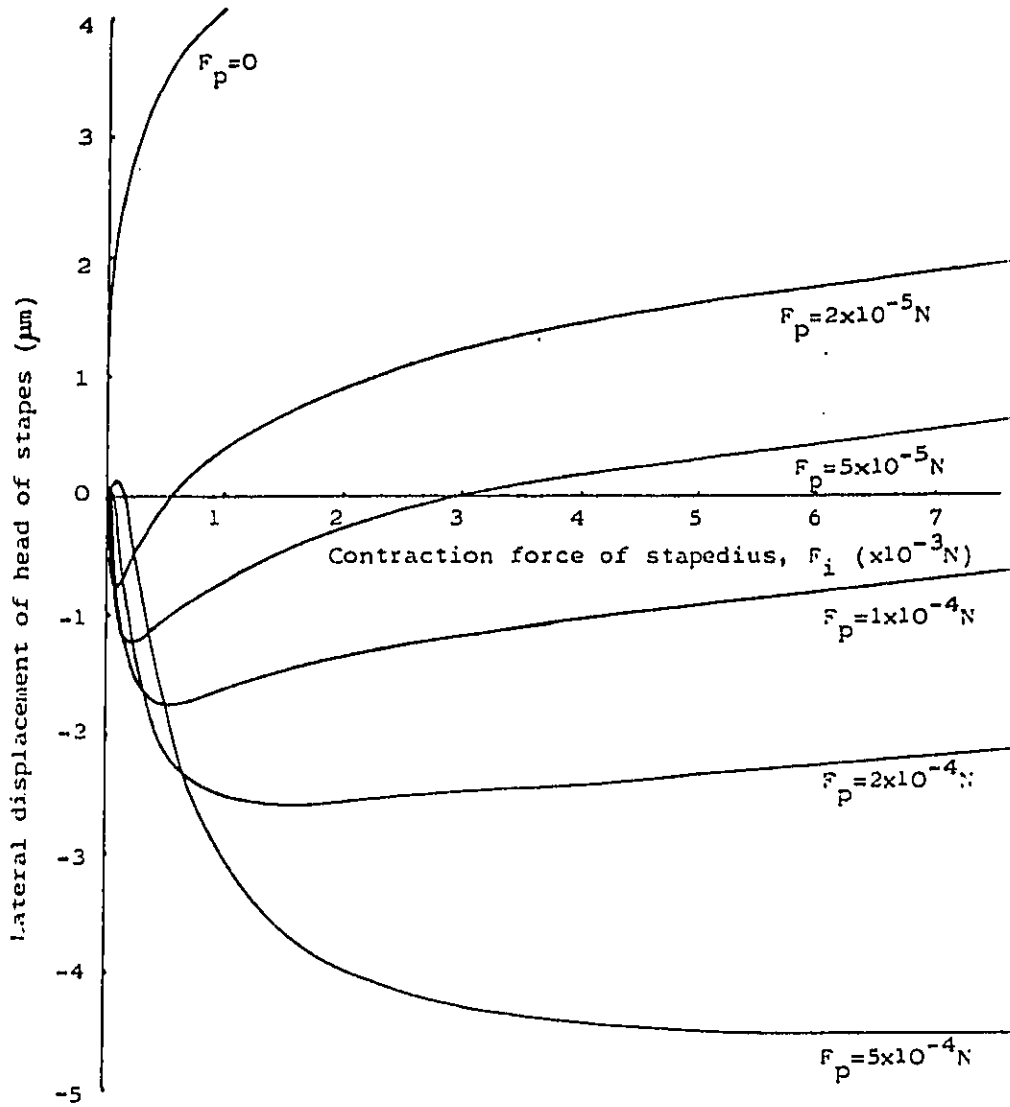
FIG. 3.7   Displacement of the head of the stapes vs stapedius
            force for various forces due to the perilymphatic fluid
            pressure. $E=0.55$ MNm^{-2}, $a=120$ μm, $p=60$ μm.
            (Tweed, 1985)

3.4 Concluding Discussion

The three models discussed in this chapter all predict that an increase in perilymphatic pressure will favour a more 'inward-going' reflex-induced TM displacement. The current study will attempt to provide experimental evidence to support this hypothesis, by indirectly varying the perilymphatic pressure using postural changes to vary the CSF pressure. Provided that subjects have patent cochlear aqueducts, this approach will allow changes in the CSF pressure, and consequent changes in perilymphatic pressure to be controlled within known limits. The magnitude and form of the observed TM displacements will also be compared with those predicted by the models as a means of verification.

MEASUREMENTS OF TYMPANIC MEMBRANE DISPLACEMENT IN RESPONSE
TO THE ACOUSTIC REFLEX

4.1   Introduction

The experimental work reported here was carried out using the
Tympanic Membrane Displacement measurement technique developed by
Marchbanks (1980).   This procedure measures the volume
displacement of the Tympanic Membrane by maintaining constant
pressure in the sealed external auditory meatus using a servo-
driven reference diaphragm in an external cavity connected
pneumatically to the ear.   The input voltage to the diaphragm is
then proportional to the volume displacement of the TM.   By this
method the TMD measurement technique provides an extremely
precise and absolute measure of TM movement under near free-field
conditions.

Marchbanks has used the TMD measurement technique to study a
number of aspects of middle ear function.   These include
Eustachian tube patency, gas absorption in the middle ear and the
acoustic reflex contraction of the ME muscles (Marchbanks 1980,
1982).   Of particular interest here is the acoustically induced
reflex contraction of the stapedius muscle (Marchbanks and Martin
1984b).   It has been found that due to high background noise
levels within the auditory meatus, ensemble averaging is an
essential feature of any TMD measurement.   The number of records
required for an ensemble average will vary between subjects and
in the same ear depending on the stimulus level relative to the
reflex threshold.   The number of records necessary to produce a
good response amplitude-time waveform is found to range from a
single sweep for a strong response to a maximum of 40 records for
weak responses at low stimulus levels.

The equipment used in this study provides various types of sound
stimuli to elicit the acoustic reflex and then measures the
subsequent TM volume displacement in either the contralateral or
ipsilateral side to the stimulated ear.   Figure 4.1 shows a
systematic model of the acoustically induced stapedial reflex
(Marchbanks and Martin, 1984a).   It can be seen from this that
the TMD measurement technique can be used to study various
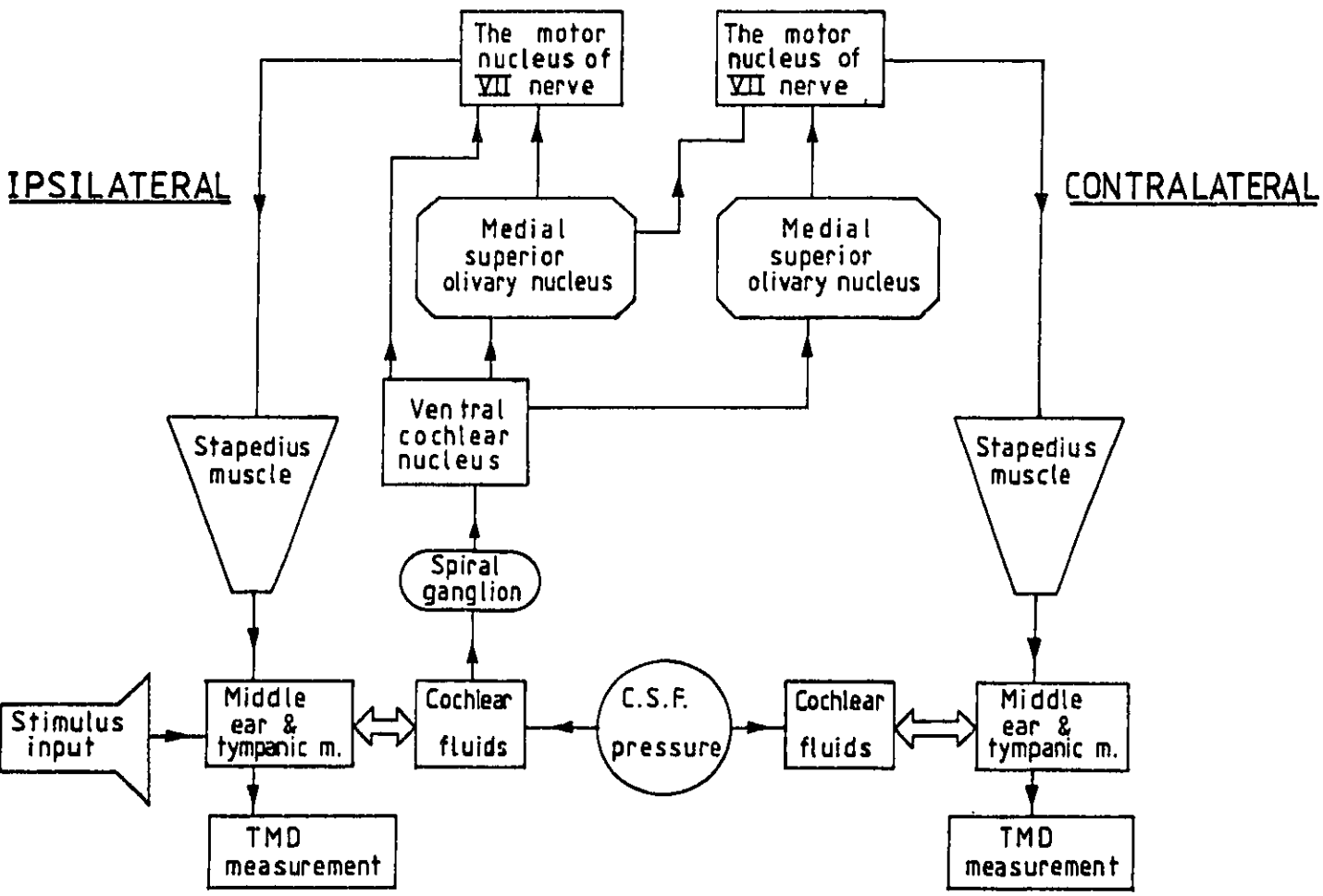aspects of the reflex system.

FIG. 4.1   SYSTEMIC MODEL OF THE ACOUSTIC INDUCED STAPEDIAL REFLEX (Marchbanks and Martin, 1984)

Broadly speaking the reflex can be separated into two main areas
of study: the mechanical interaction between the stapes and the
intracochlear fluids, and the neural transmission characteristics
of the reflex arc. This report is concerned entirely with the
former: the interaction of the intracochlear fluids with the
stapes mechanics during stapedius muscle contraction.

4.2   Movement of the Tympanic Membrane in Response to the
      Acoustic Reflex

When contraction of the stapedius muscle is elicited the TM has
been found to move in a number of different ways in normal human
subjects. The displacement can be outward, inward, or bi-
directional, that is inward then outward. Examples of these
types of volume displacement are shown in Figure 4.2. On no
occasion has the main displacement phase occurred in an outward
followed by inward pattern, although a few very small initial
outward excursions are sometimes seen. Over 2000 tests on over
400 ears have now been made and, of these, approximately 30%
display a solely outward reflex TM displacement whilst the
remaining 70% follow an inward or bi-directional configuration.

As the stimulus intensity is increased above acoustic reflex
threshold the average TM volume displacement, Vm, can become
either more inward going, more outward going or it can change
from inward-going to outward-going. Hence, to determine the
overall type of TM displacement, the reflex response for a
particular ear must be described in terms of its intensity input-
output (I/O) function.

Marchbanks and Martin (1984a) have classified these intensity
functions into three main categories, according to the stimulus
intensity above the acoustic reflex threshold at which the mean
TM volume displacement becomes positive. See Marchbanks and
Martin (1984a) for a formal definition of these categories and
Figure 4.3 for examples of the three categories.

4.3   Effect of Intra-Cochlear Fluid Pressure on the Acoustic
      Reflex Induced Tympanic Membrane Displacement

An important parameter that has been found to effect the
configuration of the TM volume displacement due to stapedial
muscle contraction is the intracochlear fluid pressure, as
predicted by the mathematical models discussed in chapter 3.

23
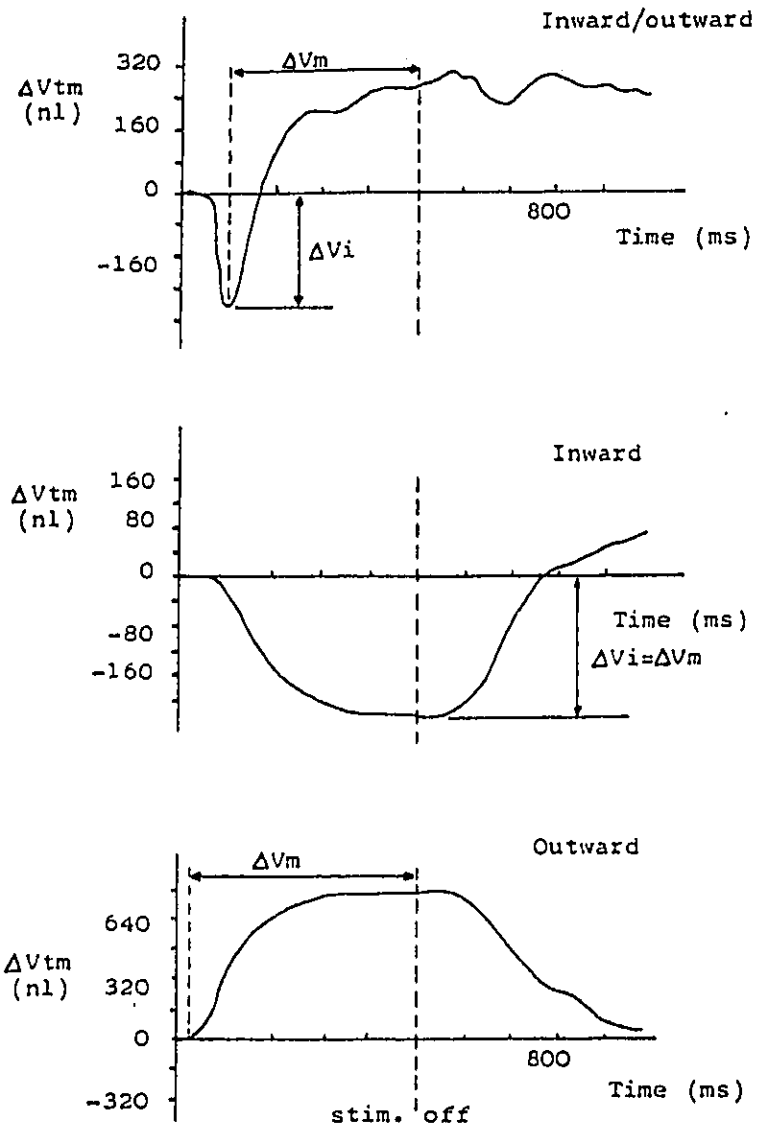
Fig.4.2 Stapedial reflex TM displacement configurations.
(Marchbanks and Martin, 1984)

EXAMPLES OF TYPES OF INTENSITY FUNCTION

ΔVm

Ia
Ib

Type I

dB re. threshold

ΔVm

IIa

Type II

dB re. threshold

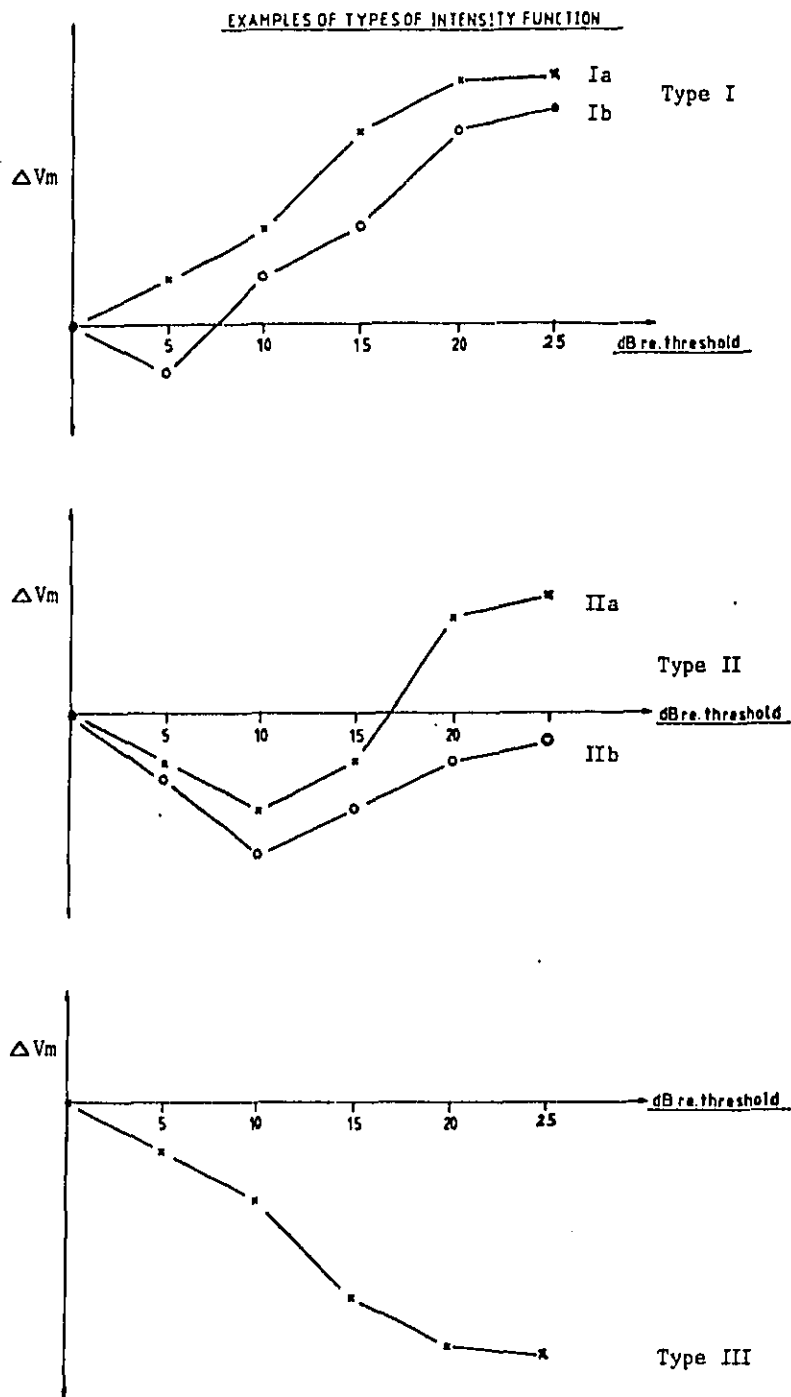IIb

ΔVm

dB re. threshold

Type III

FIG. 4.3   EXAMPLES OF TYPES OF INTENSITY FUNCTION.
(Marchbanks and Martin, 1984)

Klockhoff (1966) was one of the first to report that the
stapedius reflex response was influenced by the intracochlear
fluid pressure. He measured changes in the acoustic impedance of
the ears of both humans and animals in response to the acoustic
reflex. Brask (1978), during extratympanometric pressure
investigations in normal human subjects, noticed that the
position of the subjects, i.e. whether they were sitting upright
or recumbent, affected the direction of the pressure change in
the enclosed external meatus during stapedial contraction.

As already discussed in detail, body position is also known to
affect cerebrospinal fluid pressure and, assuming the cochlear
aqueduct is patent, this can be transmitted to the intracochlear
fluids. Brask carried out a simple experiment on a few subjects
in which they were moved from the sitting to the recumbent
position and the meatal pressure change during stapedial
contraction was measured every five minutes. Figure 4.4 shows
the results for one subject. In this case the amplitude of the
pressure change stabilized after about 20 minutes, although the
response became similar to the original response immediately the
subject was returned to the sitting position.

Densert et al (1977) investigated human temporal bones, in which
the volume displacement of the TM was measured for various forces
applied to the stapedius tendon to simulate the stapedial reflex
for a range of intracochlear fluid pressures. Generally the TMD
was reduced, and in one case became a negative displacement, when
a positive intracochlear fluid pressure was applied. Figure 4.5
summarises their results for an intra-cochlear fluid overpressure
of 150 mm water compared to the displacement obtained for zero
overpressure.

Marchbanks and Martin (1984a) performed an experiment using the
TMD measurement technique in which the intensity function of the
TMD in response to the acoustic reflex was measured in both the
sitting position and the recumbent position on ten subjects.
Figure 4.6 shows their results in terms of a graph of the mean
TM displacement in the recumbent position minus that in the
sitting position for increasing stimulus intensity above the
reflex threshold. Figure 4.7 illustrates the maximum inward
volume displacement of the TM during stapedial contraction.

Marchbanks and Martin (1984a) have investigated the abnormally
high intracochlear fluid pressure which is thought to accompany
Meniere's Syndrome. They have shown that the mere presence of
an inward going reflex displacement in the sitting position is
not necessarily an indication of high intracochlear fluid
pressure, as a certain proportion of normal subjects naturally

24

Minutes

A	0
B	5
C	10
D	15
E	20
F	25
G	

Time (ms)
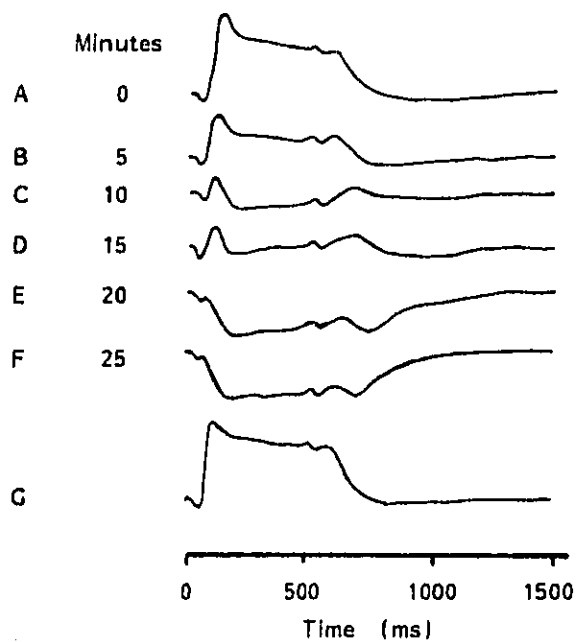
FIG. 4.4   MEATAL PRESSURE CHANGE DURING STAPEDIAL
CONTRACTION ELICITED DURING POSTURE CHANGE.
(Brask, 1978)   A - Sitting,   B → F - Recumbent,
G - Sitting
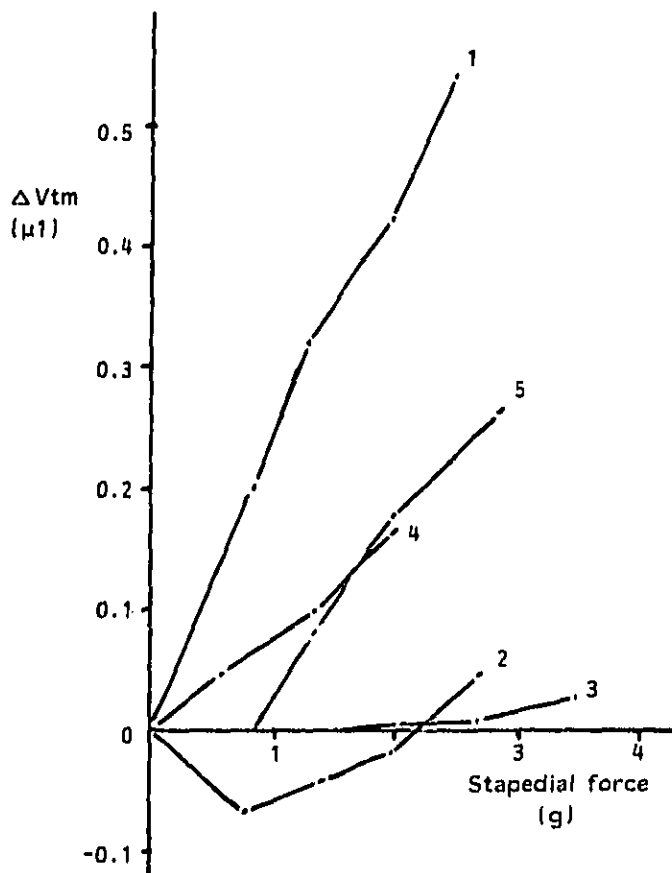
FIG. 4.5   THE VOLUME DISPLACEMENT OF THE TYMPANIC MEMBRANE
AS A FUNCTION OF THE FORCE APPLIED TO THE
STAPEDIUS TENDON WITH A PERILYMPHATIC FLUID OVER-
PRESSURE OF 15 cm H_2O IN FIVE HUMAN TEMPORAL BONES.
(Densert et al, 1977)
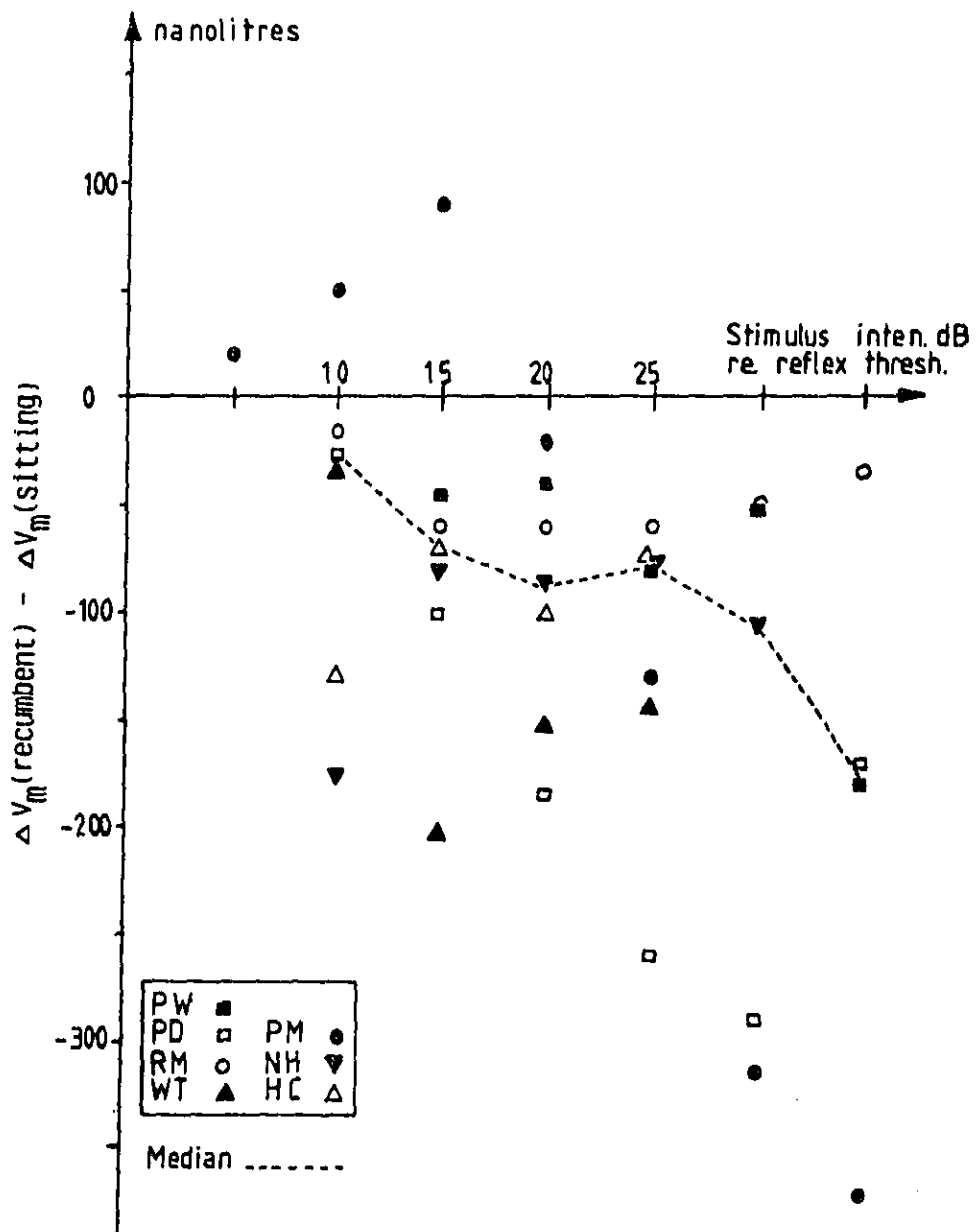
FIG. 4.6   THE CHANGE IN MEAN TYMPANIC MEMBRANE VOLUME DISPLACEMENT
DUE TO MOVEMENT FROM THE SITTING TO RECUMBENT POSITION
AS A FUNCTION OF STIMULUS INTENSITY (Marchbanks and Martin,
1984).
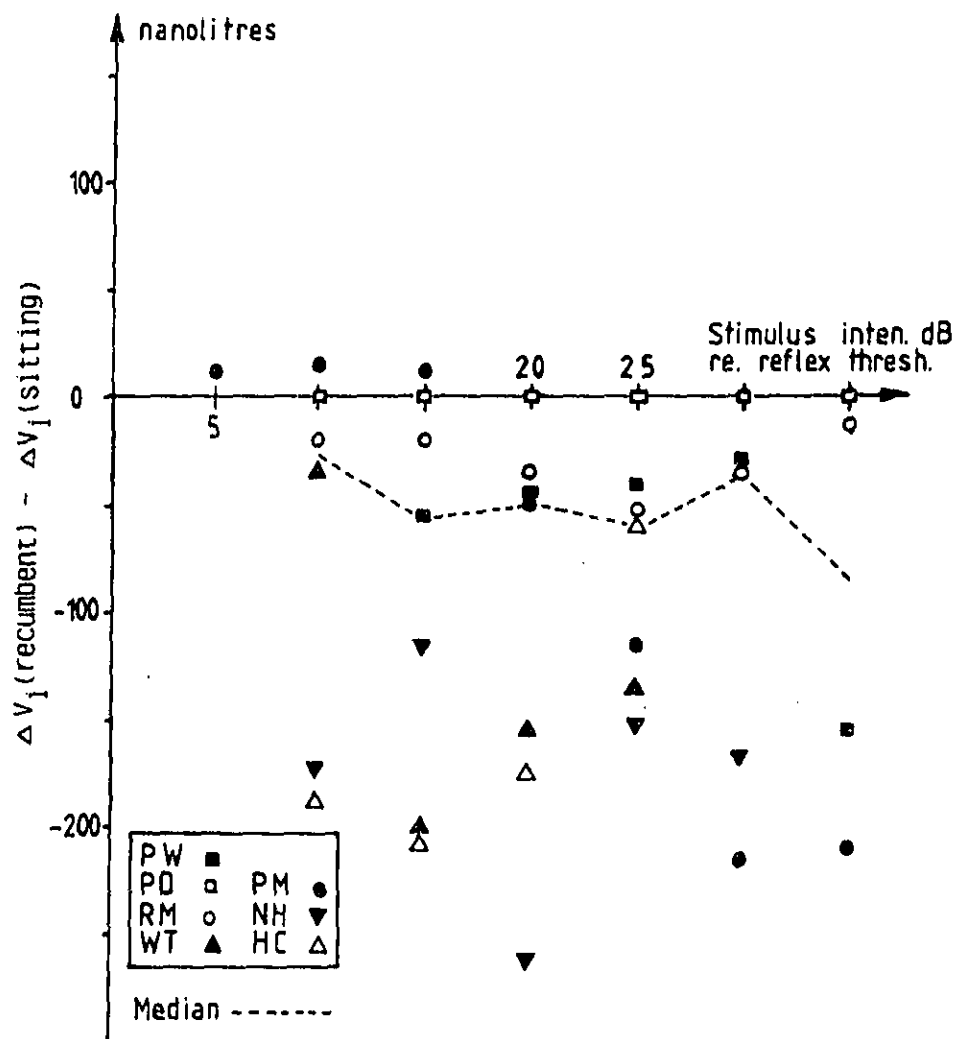
FIG. 4.7   THE CHANGE IN MAXIMUM INWARD TYMPANIC MEMBRANE VOLUME
DISPLACEMENT DUE TO MOVEMENT FROM THE SITTING TO RECUM-
BENT POSITION AS A FUNCTION OF STIMULUS INTENSITY.
(Marchbanks and Martin, 1984)

possess inward-going reflex displacements. This proportion
decreases however as the acoustic stimulus intensity is increased
above reflex threshold.

So as to emphasis the 'inward-goingness' of reflex displacement
configurations, Marchbanks and Martin (1984a) defined a
parameter, called the Inward Displacement Index (IDI), which is
defined as the ratio of the mean volume displacement of the TM to
the maximum inward volume displacement, i.e. $\Delta Vm/\Delta Vi$. All
inward displacing reflex configurations, with no outward going
tendencies, fall within the group with IDI values greater than
0.8. This is the predicted form of the configurations at reflex
saturation for abnormally high intra-vestibule pressures.

In the practical test situation the stimulus level at which
reflex saturation occurs is difficult if not impossible to
ascertain. Consequently a decision on the abnormality of the
configuration is made with reference to the reflex supra-
threshold stimulus level. In an experiment on 50 normal
subjects (100 ears) Marchbanks and Martin (1984a) measured the
IDI in 5 dB increments above reflex threshold. The subjects
were in the sitting position and the contralateral reflex-induced
TMD was measured. At 30 dB above reflex threshold only 3% of
the ears had an IDI greater than 0.8 This value of IDI is
proposed as a criterion for detecting abnormally high
intracochlear fluid pressure in patients suspected of having
Meniere's Disease.

CHAPTER 5

EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF BODY POSITION ON TYMPANIC MEMBRANE DISPLACEMENT INDUCED BY THE ACOUSTIC STAPEDIAL REFLEX

5.1 Introduction

The aim of the experiment was to investigate the relationship between the volume displacement of the TM during stapedial muscle contraction and variations in intracochlear fluid pressure. Body position was chosen as the means for varying the intracochlear fluid pressure and, although this could not be monitored directly, the experimental evidence available (discussed in Chapter 2) shows that a relationship exists between body position and CSF and perilymphatic fluid pressures. Hence the experiment was designed to investigate the effect of body position on the acoustic reflex-induced displacement of the TM in normal human subjects.

5.2 Experimental Design

The experiment was designed to compare the reflex TM volume displacement configuration obtained in the sitting position with that produced when the subject was moved to angles of 30°, 60° and 90° to the upright position, where 90° corresponds to the subject being recumbent. It was also decided to investigate the relationship between the TM volume displacement configuration with time at each position over a period of 20 minutes.

The stimulus level chosen for the main part of the experiment was 15 dB above reflex threshold. This level was a compromise between the requirement of obtaining a good signal-to-noise ratio in the TMD responses and not having to reject too many subjects due to the stimulus being too loud. For a subject with an acoustic reflex threshold of 95 dB SPL, the equivalent continuous noise level (referred to 60 minutes) of the stimulus for the main experimental session was 94.6 dB.

Since it is possible to measure TM displacements ipsilaterally to the stimulus, and in general a much stronger response is obtained in this case compared to contralateral recordings, ipsilateral TMD measurements were employed throughout the experiment.

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A number of preliminary tests were required on each subject. It was necessary to check that the intra-cochlear fluid pressure equilibrated within a few minutes of moving from the recumbent to the sitting position. Also, to determine the reflex threshold, the reflex I/O function had to be measured. To complete all the preliminary tests and the main experiment in one session would have taken too long and exposed the subjects to excessive noise. Therefore the measurements were carried out in two sessions, the preliminary test being undertaken in the first session and the main experiment during the second.

The experimental design was balanced to detect differences between males and females, left and right ears and the order of the angles to which the subjects were moved.

5.3 Subjects

In total 24 normal subjects, 12 males and 12 females, were tested with ages between 18 and 30 years. None of the subjects had any history of ear disease or vertigo, and none had upper respiratory tract or ear infections within two weeks prior to testing.

5.4 Screening of Subjects

The subjects were screened for normal hearing with pure tone audiometry, and those with hearing levels greater than 20 dBHL (re ISO 1964) in the range 250 Hz to 4000 Hz were rejected. Likewise the ME function of each subject was evaluated with tympanometry, and those who had ME pressures outside the range +20 to -50 daPa or a static compliance at 220 Hz outside the range 0.3 to 1.5 ml were rejected. Immittance audiometry was also carried out on each subject to ensure that the acoustic reflex at 1000 Hz could be elicited at or below the upper limit of normality of 95 dB SPL. If this was not the case the experiment would expose the subjects to excessive noise levels, thus introducing the possibility of temporary threshold shift.

The ME pressure was measured in each ear for both the sitting and recumbent positions to ensure that there was a pressure difference between the two of less than 10 daPa. The reason for this was that a change in ME pressure on changing posture can in certain subjects affect the resting position of the TM (Casselbrant et al, 1977). This in turn could produce different reflex-induced displacement configurations of the TM for different postures that were not actually caused by the change in the intracochlear fluid pressure.

5.5 Instrumentation

Measurements were made using the TMD measurement system developed by Marchbanks (1980). This technique has been incorporated into a 'Computerised Audiometric System', an instrument package which provides an integrated approach to certain audiometric tests (Marchbanks and Martin, 1985). This system was used to set the stimulus and test parameters, to run the tests on each subject automatically, and to store the record of each reflex TM displacement for subsequent future analysis.

The duration of the simulus was set to 0.7 seconds, as this is the minimum period necessary for the stapedius muscle to contract and reach its steady state value in most subjects. Obviously the shorter the stimulus duration the less noise exposure the subject would receive. The stimulus frequency chosen was 1000 Hz, being the frequency at which most investigations of the acoustic stapedial reflex has been made. The rise time of the stimulus was 60 ms, which is relatively slow but was chosen so that the contraction of the stapedius muscle would more closely approximate to that predicted by the static model of stapes motion produced in a previous study (Tweed, 1985). Again, this is a compromise. A 60 ms rise time does not totally eliminate the dynamic effects of the muscle contraction, but for slower stimulus rise times the detailed time-course of the reflex will become increasingly masked by low-frequency physiological and atmospheric noise.

5.6 Procedure

In the preliminary experimental session each subject was screened for normal auditory function as described in section 5.4. Then the headset of the TMD measurement system was placed on the subject whilst sitting in the upright position, and the transducer probe was sealed into the external auditory meatus of the prescribed ear and checked for air leaks. The reflex intensity I/O function was then measured by obtaining ensemble-averaged TMD response waveforms starting at a stimulus of 100 dBHL, followed by 110 and 115 dBHL, and then by working down from 100 dB in 10 dB steps until the reflex threshold had been determined. The subject was then moved to the recumbent position for 20 minutes and instructed to relax and to move as little as possible. Finally with the headset still in place, the subject was moved back to the sitting position and the averaged reflex TMD response waveforms were again determined at 5 minute intervals for 20 minutes.

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The main experimental session was conducted on a separate day, and followed the measurement procedure outlined in Figure 5.1. With the subject in the upright sitting position the TMD measurement device was attached and sealed to the prescribed ear, as described above. The subject was then instructed to relax for 8 minutes. After this time the averaged reflex TMD response waveform was recorded for a stimulus level of 15 dB above the reflex threshold for that particular ear, as found in the preliminary experimental session. After 10 minutes the subject was moved to the first body position as indicated by the balanced experimental design. After 11 minutes, and after every subsequent 5 minute interval, an averaged reflex TMD measurement was made, until at 31 minutes the subject was again moved into the upright sitting position. After another 8 minutes in this position the reflex TMD measurement was again made.

The test session proceeded in this manner following the design in Figure 5.1 until all three changes in posture had been investigated.

Time (minutes)	Action
0 - 8	Sitting
8 - 10	Reflex TM volume displacement measure
10 - 11	Move to position 1
16	Reflex TM volume displacement measure
21	"
26	"
31	"
31 - 32	Move to sitting position
32 - 40	Sitting
40 - 42	Reflex TM volume displacement measure
42 - 43	Move to position 2
48	Reflex TM volume displacement measure
53	"
58	"
63	"
63 - 64	Move to sitting position
64 - 72	Sitting
72 - 74	Reflex TM volume displacement measure
74 - 75	Move to position 3
80	Reflex TM volume displacement measure
85	"
90	"
95	"

FIG. 5.1   PROCEDURE FOR SECOND (MAIN) EXPERIMENT.

EXPERIMENTAL RESULTS

6.1 Changes in Reflex-Induced Displacements of the Tympanic Membrane on Moving from the Recumbent to the Sitting Position

The aim of the first part of the experiment was to examine whether the reflex TMD response waveform changed significantly with time after the subjects were moved from the recumbent position to the sitting position. Each subject lay in the recumbent position for 20 minutes to allow labyrinthine fluid pressure to equilibrate with CSF pressure and then, after sitting up, the averaged reflex-induced TMD waveforms were recorded at 5 minute intervals over a 20 minute period. The two waveform parameters Vm and Vi were then determined from each of these responses and the changes in these parameters, ΔVm and ΔVi respectively, were calculated. The average values of ΔVm and ΔVi are plotted against time in Figure 6.1 and shown in Table 6.1.

TABLE 6.1 Average and Standard Deviation Values of the Mean Tympanic Membrane Diplacement, ΔVm, and the Maximum Inward Tympanic Displacement, ΔVi, over 20 Minutes After Sitting Up from the Recumbent Position.

	Time minutes	Mean nl	Standard Deviation nl
ΔVm	5	8.17	252.8
	10	36.54	240.4
	15	45.25	256.2
	20	68.75	256.8
ΔVi	5	−214.62	216.1
	10	−181.54	200.1
	15	−197.17	235.6
	20	−162.08	165.7
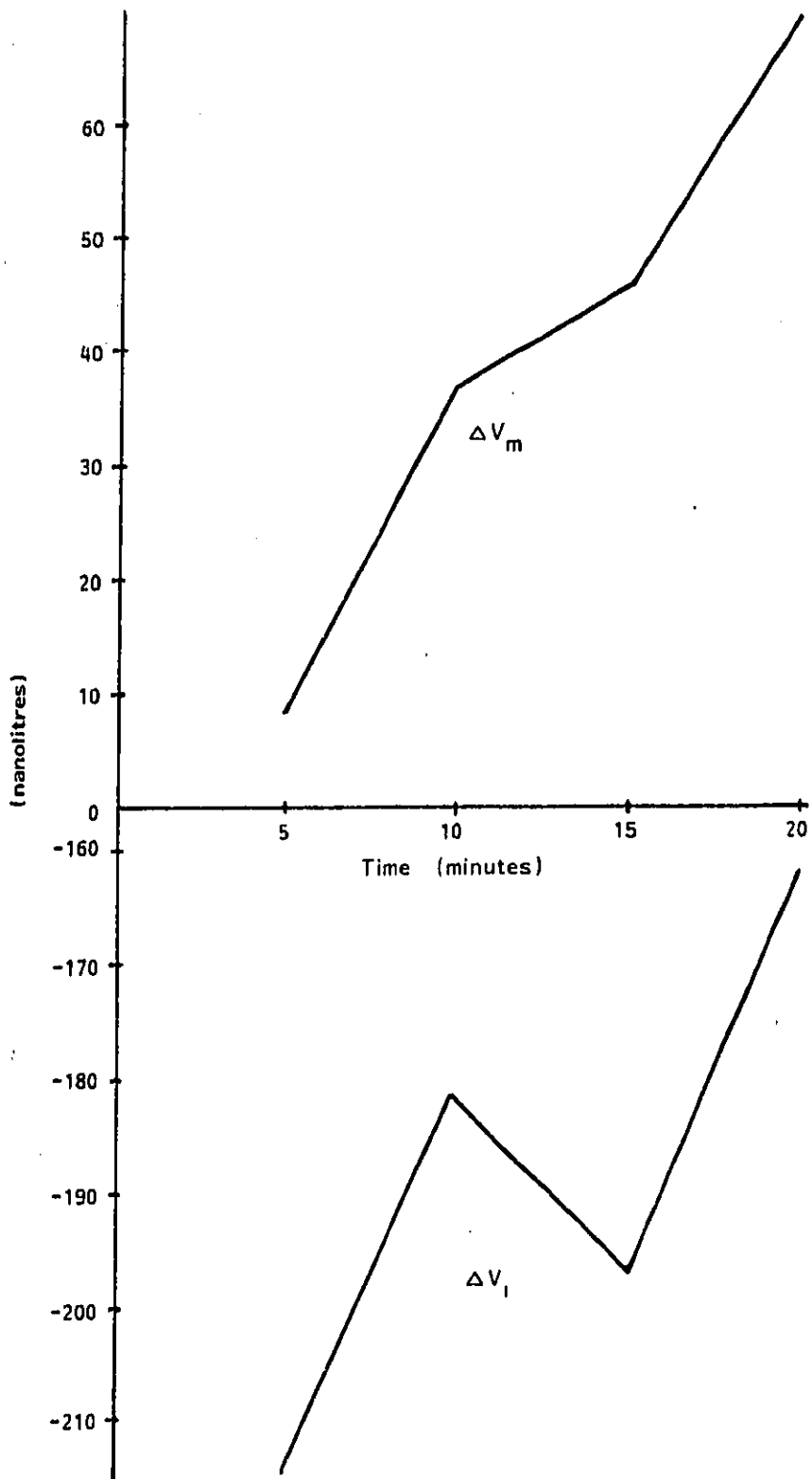
FIG. 6.1   THE CHANGE IN ΔV_m AND ΔV_i ON MOVING FROM THE
RECUMBENT TO THE SITTING POSITION PLOTTED
AGAINST TIME.

Because some of the subjects had inward, some outward and some
biphasic reflex displacement configurations, the range in ΔVm
and ΔVi at each time interval was very large, as indicated
by the large standard deviations shown in Table 6.1. This
tended to obscure any trend with time. Using Analyses of
Variance (ANOVAR) however, the between-subject variance can be
allowed for.

Tables 6.2 and 6.3 give the ANOVAR summary tables for ΔVm and
ΔVi respectively. They show that even when the between-subject
variance is removed, time is still only a significant variable at
about the 10% level. Thus, although there appears from Figure
6.1 to be a trend in the average values of the parameters ΔVm
and ΔVi with time 5 minutes after moving the subjects to the
sitting position, this trend is only confirmed at a borderline
statistical significance.

TABLE 6.2 Summary of Analysis of Variance of the Mean Tympanic
Membrane Displacement Change, ΔVm, with Time.

Source of Variance	DF	SS	MS	F-Ratio
Between-Subject	23	5320613	231331	31.53
Time	3	45097	15032	2.05
Residual	69	506250	7337	
Total	95	5871959		

TABLE 6.3 Summary of Analysis of Variance of the Change in
Maximum Inward Tympanic Membrane Displacement, ΔVi, with Time.

Source of Variance	DF	SS	MS	F-Ratio
Between-Subject	23	3153814	137122	12.63
Time	3	36081	12027	1.11
Residual	69	749113	10857	
Total	95	3939008		

6.2 Changes in Tympanic Membrane Displacement on Moving from the Sitting Position to Three Angles of Body Position

The aim of the second part of the experiment was to investigate how the reflex TMD response configuration changed over a 20 minute period when the subjects were moved from the sitting position to one of three body positions at the following angles (A): $30^{\circ}, 60^{\circ}$ and 90° to the vertical.

Figures 6.2 and 6.3 show the mean values for the 24 subjects of ΔVm and ΔVi plotted against the parameter $(1-\cos(A))$ for the 4 time intervals. The parameter $(1-\cos(A))$ is proportional to the vertical height through which the subject's head traverses on changing posture through the angle (A). Included in the means of ΔVi are the zero values corresponding to subjects who had an outward-going reflex configuration.

Figures 6.4 and 6.5 show the same data plotted against time for the three angles.

TABLE 6.4 Average and Standard Deviation Values of the Mean Change in Tympanic Membrane Displacement, ΔVm, with Time on Moving from the Sitting Position to Each of Three Angles to the Vertical.

Angle degrees	Time minutes	Mean ΔVm nl	Angle Mean nl	Standard Deviation nl
90	5	147.4		116.6
	10	155.3		126.6
	15	170.5	163.7	175.9
	20	181.7		169.3
60	5	10.2		143.8
	10	37.2		120.5
	15	93.5	48.4	152.7
	20	52.8		161.3
30	5	9.1		124.2
	10	45.1		160.1
	15	54.7	32.5	189.4
	20	21.1		155.1
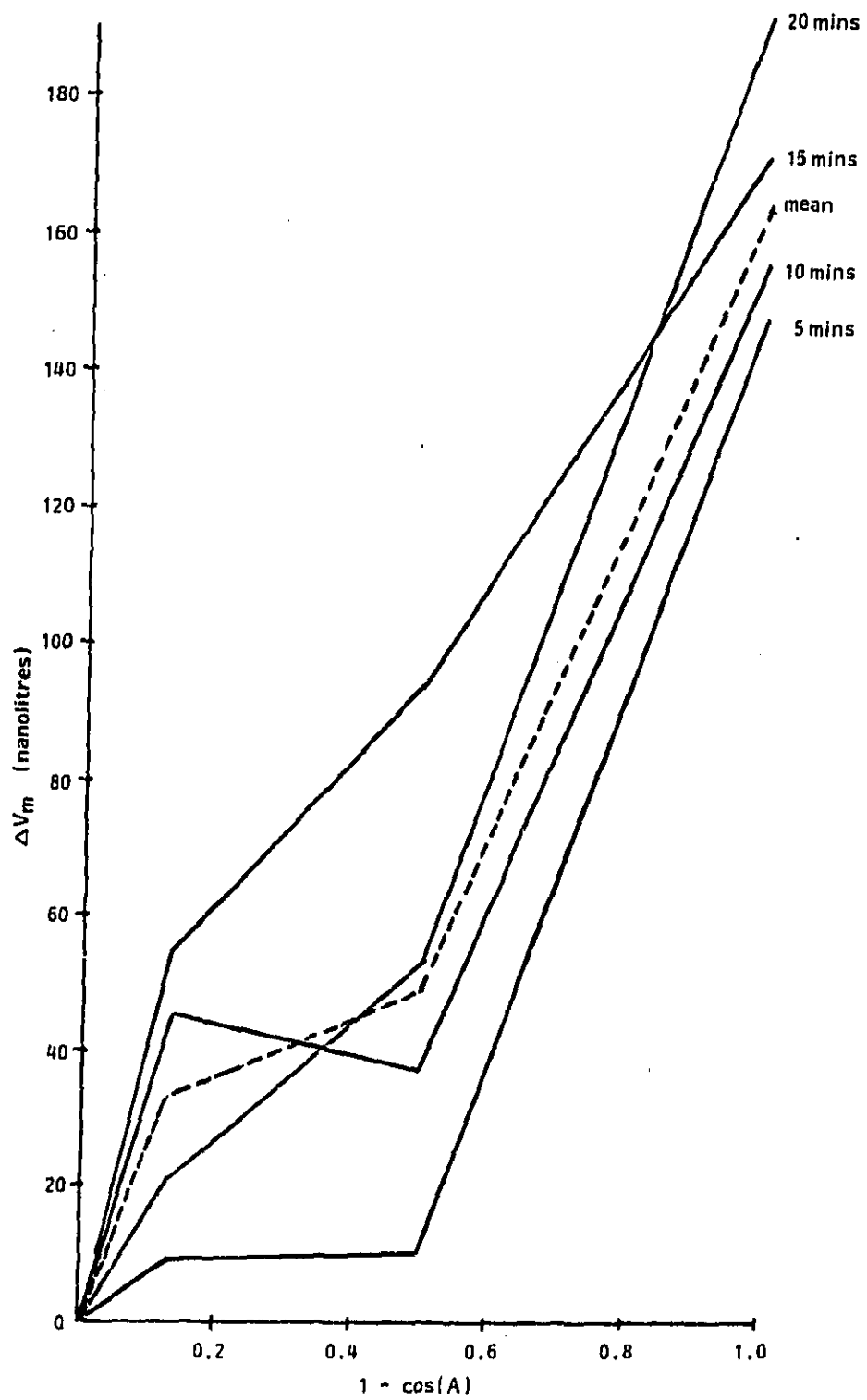
FIG. 6.2   THE CHANGE IN ΔV_m ON MOVING FROM THE SITTING
POSITION TO THE ANGLES 30°,60°,90° TO THE VERTICAL
PLOTTED AGAINST $1 - \cos(A)$ OVER A 20 MINUTE PERIOD.
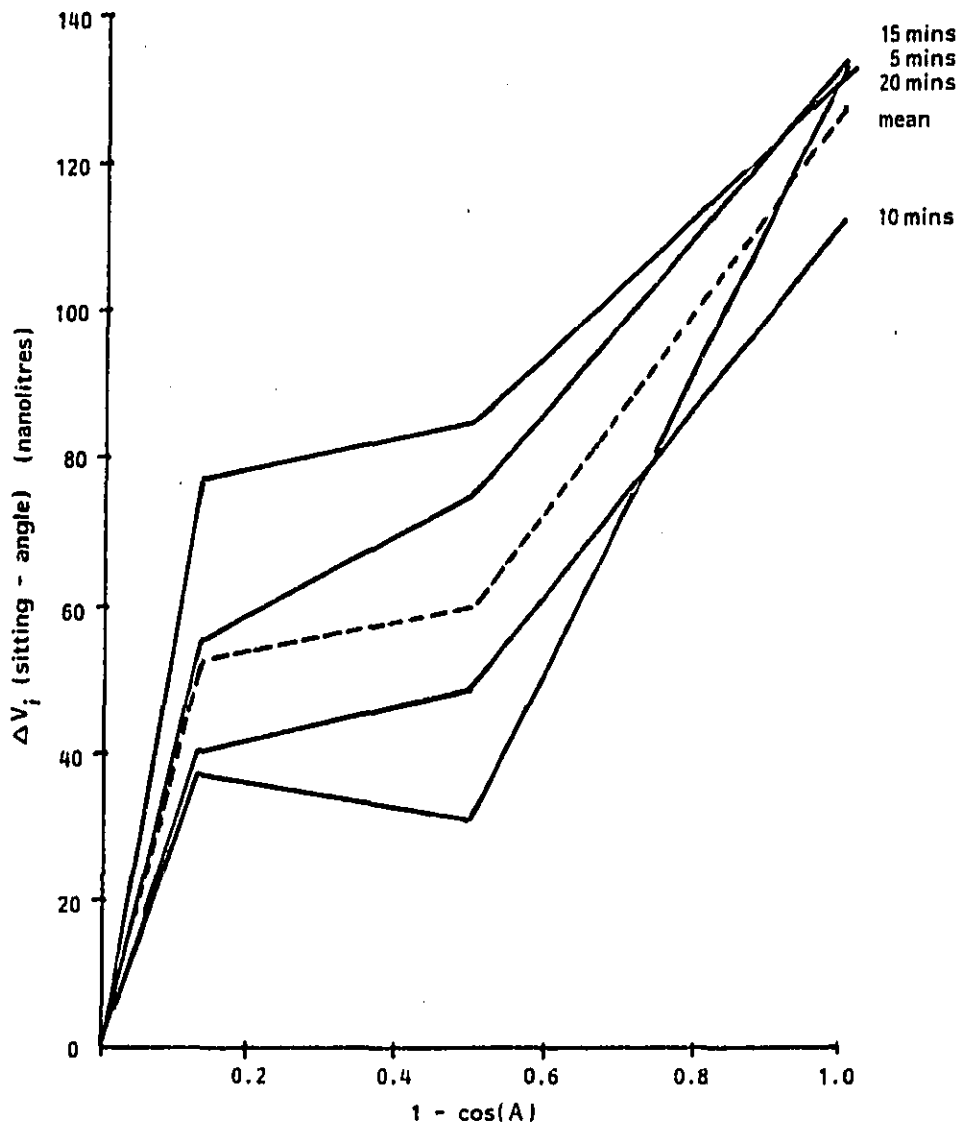
FIG. 6.3   THE CHANGE IN ΔV_j ON MOVING FROM THE SITTING
            POSITION TO THE ANGLES 30°,60°,90° TO THE VERTICAL
            PLOTTED AGAINST 1 - cos(A) OVER A 20 MINUTE PERIOD.
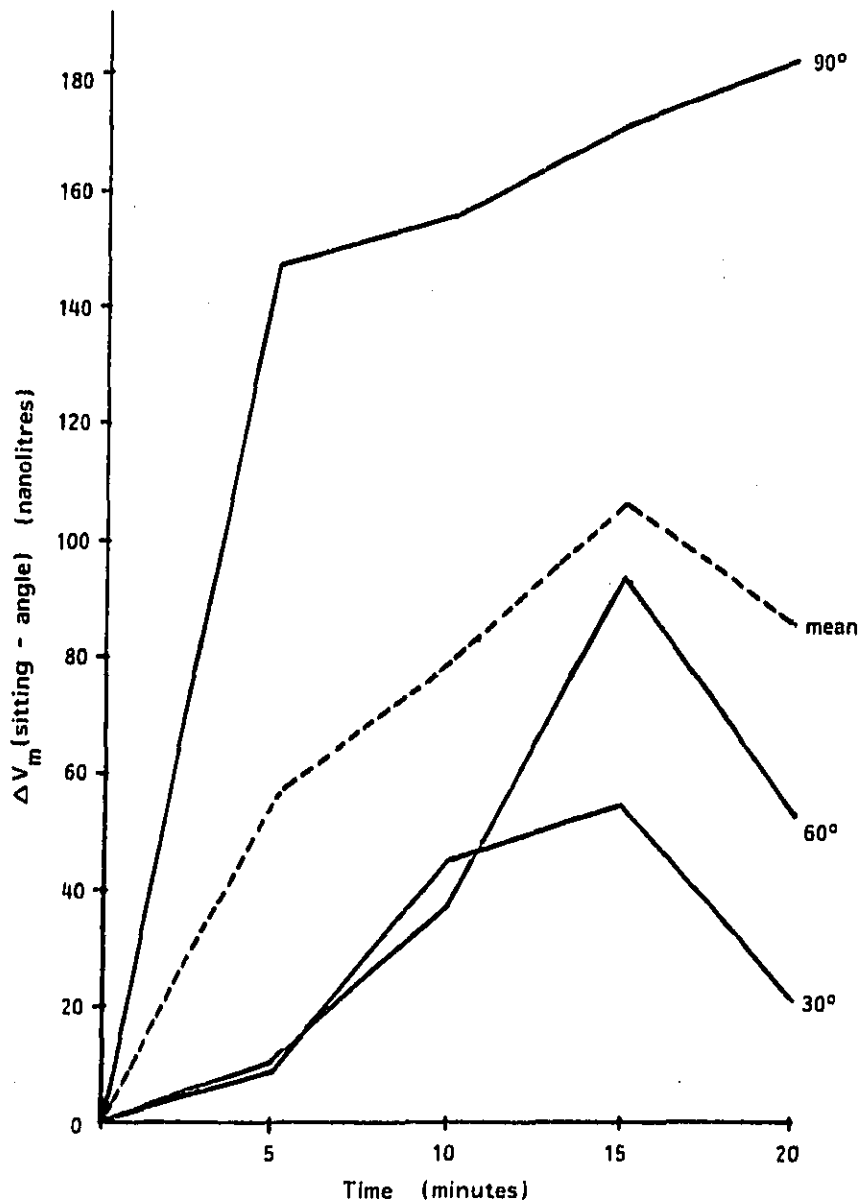
FIG. 6.4   THE CHANGES IN V_m ON MOVING FROM THE SITTING
POSITION TO THE THREE ANGLES 30°,60°,90° TO THE
VERTICAL PLOTTED AGAINST TIME.
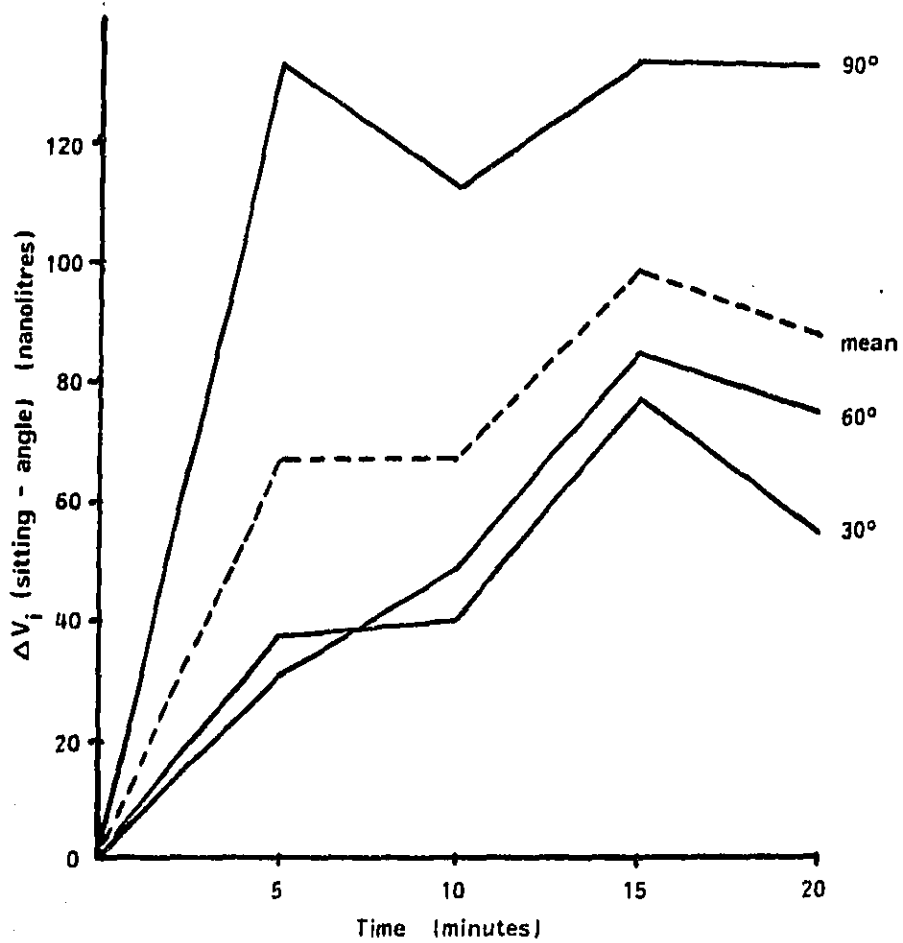
FIG. 6.5   THE CHANGE IN ΔV_i ON MOVING FROM THE SITTING
POSITION TO THE THREE ANGLES 30°,60°,90° TO THE
VERTICAL PLOTTED AGAINST TIME.

TABLE 6.5 Average and Standard Deviation Values of the Changes in Maximum Inward Tympanic Membrane Displacement, ΔVi, with Time on Moving from the Sitting Position to Each of Three Angles to the Vertical.

Angle degrees	Time minutes	Mean ΔVi nl	Angle Mean nl	Standard Deviation nl
90	5	132.4		147.0
	10	112.1		130.7
	15	133.2	127.4	142.1
	20	131.9		154.7
60	5	30.6		124.4
	10	48.6		119.1
	15	84.4	59.5	151.7
	20	74.3		146.6
30	5	37.0		67.3
	10	40.1		85.8
	15	77.0	52.2	121.4
	20	54.5		115.5

Tables 6.4 and 6.5 list the means and standard deviations of ΔVm and ΔVi respectively for the 4 time intervals for each of the three angles. It can be seen that the standard deviations are large compared to the values of the means. Again, this is principally due to the large inter-subject variance, which can be taken into account using analyses of variance.

Tables 6.6 and 6.7 summarise the ANOVAR tables for ΔVm and ΔVi respectively. Not only has the between-subject variance been removed from the total sum of squares but also that due to male-female difference, left/right ear difference, the difference between the angles and times tested, and also the order in which the angles were tested.

For both ΔVm and ΔVi the between-subject variance, angle (A) and angle test order variances are all significant ($p < 0.01$). In the case of ΔVi the variance due to male-female differences is also significant, although this is probably due to the large proportion of males tested having outgoing reflex TMD responses, which results in zero values being found for ΔVi. If only the biphasic and inward going TMD responses are compared no difference between males and females is found ($p < 0.01$).

TABLE 6.6 Summary of Analysis of Variance of the Change in Mean Tympanic Membrane Displacement, ΔVm, on Moving from the Sitting Position to Each of Three Angles to the Vertical.   The Least Significant Difference for the Three Angles is 51.9.

Source of Variance	DF	SS	MS	F-Ratio
Between-Subject	23	1836033	79828	5.32
Sex	1	5425	5425	0.36
Angle (A)	2	984388	492194	65.59
Time	3	93847	31282	2.08
Angle Order	5	709891	141978	9.46
Left/Right	1	28084	28084	1.87
Residual	252	3782025	15008	
Total	287	7439693		

TABLE 6.7 Summary of Analysis of Variance of the Change in Maximum Inward Tympanic Membrane Displacement, ΔVi, on Moving from the Sitting Position to Each of Three Angles to the Vertical.   The Least Significant Difference for the Three Angles is 36.3.

Source of Variance	DF	SS	MS	F-Ratio
Between-Subject	23	2020847	87863	11.93
Sex	1	279129	279129	37.90
Angle (A)	2	330554	165277	22.44
Time	3	52305	17435	2.37
Angle Order	5	359093	71819	9.75
Left/Right	1	36360	36360	4.94
Residual	252	1855625	7364	
Total	287	4933913		

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The order in which the three body angles were tested was found to be significant for both ΔVm and ΔVi. Examination of the ΔVm means for the six combinations of angle given in Table 6.8 shows that it is the 60-90-30° combination that is significantly different from the rest, producing a mean negative change in ΔVm.

TABLE 6.8 Average Values of the Mean Tympanic Membrane Displacement Change, ΔVm, for Six Combinations of Posture Angle.

Angle Combination degrees	Mean ΔVm nl
90-30-60	1300
30-90-60	944
90-60-30	796
30-60-90	1613
60-30-90	1428
60-90-30	-159

This is due to the fact that 3 of the 4 subjects tested with this combination showed a negative rather than a positive change in ΔVm on moving from the sitting position through angle (A) to the test position. Presumably if more subjects had been tested the angle test order would not be significant.

The two variables that the experiment was primarily aimed at investigating were the body position (angle A) and the time.   As discussed above, time was only seen as a marginally significant variable in this analysis due to the very large variances associated with the method of quantifying the TMD responses. Changes in body angle, however, do demonstrate stronger relationships and deserve further investigation.   Comparing the least significant differences (LSD) (5% level of t-distribution) for ΔVm and ΔVi with the differences between the means in Tables 6.4 and 6.5, showed that the average ΔVm(sitting-90°) over the 20 minutes was significantly different from ΔVm(sitting-60°) and from ΔVm(sitting-30°).   Comparison of these TMD parameters with no change, ie when ΔVm and ΔVi are zero, indicated that the average ΔVm(sitting-0°) and ΔVm(sitting-30°) were not significantly different from zero. However, ΔVm(sitting-60°) at 15 minutes and 20 minutes, and for ΔVm(sitting-30°) at 15 minutes were significantly different.

The change in maximum inward displacement, ΔVi, was found to be a far more sensitive parameter than ΔVm, as its value for all the angles was significantly different from zero at every time interval, except after 5 minutes at 60o.

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To investigate these complex relationships between ΔVm, ΔVi, body angle and time more closely, polynomial regression analyses were undertaken using the angle and time in turn as predictors. The results using body angle as the predictor are summarised in Tables A1 and A2 in the Appendix, see also Figures 6.2 and 6.3. The analyses of ΔVm and ΔVi using time as the predictor are summarised in Tables A3 and A4 in the Appendix, see also Figures 6.4 and 6.5. As can be seen, these analyses support the previous findings but, owing to the relatively small number of results for each condition and the large variance of ΔVm and ΔVi, they provide no further significant insight into the details of the individual relationships.

CHAPTER 7

DISCUSSION

The main finding of the first part of the experiment was that, after 20 minutes in the recumbent position and then sitting up, the subjects' reflex TMD response waveform returned to the normal (sitting) configuration within 5 minutes. There was no further change in ΔVi with time of statistical significance over the next fifteen minutes. However, as shown in Figure 6.1, the mean values of the other parameter ΔVm did tend to increase monotonically with time over the latter 15 minutes and an ANOVA indicated that time was a factor of borderline significance in this case. Indeed the values of both ΔVm and ΔVi did tend to become more positive over the twenty minutes of the experiment. It may be that a larger subject sample would show this increase to be statistically significant despite the very large between-subject variance caused by the different TMD waveform configurations. For the purpose of this experiment however, it was reasonable to assume that the response configuration reached a steady state within 5 minutes of moving back to the sitting position. This condition was necessary for the second part of the experiment.

The findings of the second part of the experiment indicated that when subjects were moved from the sitting position to one of three angles (A), there was a decrease in both ΔVm and ΔVi. In other words both $[\Delta Vm(sitting)-\Delta Vm(A)]$ and $[\Delta Vi(sitting)-\Delta Vi(A)]$ were positive. This decrease was significant for angles of 30°, 60° and 90° to the upright after 15 minutes. When subjects were moved to 90°, however, both $\Delta Vm(sitting-90^{\circ})$ and $\Delta Vi(sitting-90^{\circ})$ were significantly different from zero after 5 minutes. Nevertheless once this change had occurred, the change in ΔVm and ΔVi over the next 15 minutes was not statistically significant.

Hence, for the changes in posture employed in this experiment, the observed changes in the response waveform parameters ΔVm and ΔVi occurred mainly in the first 5 minutes. Nevertheless there appeared to be a trend with time of less significance over the full 20 minutes of each part of the experiment. These results are in agreement with the previous findings of Brask (1978) who measured the meatal pressure change during stapedial contraction in the sitting and recumbent positions, as shown in Figure 4.4. Similar results have been reported by Marchbanks and Martin

(1984a), who measured the TM volume displacement in the sitting and recumbent positions, as illustrated in Figures 4.6 and 4.7.

The question of how these results relate to the CSF pressure, which is affected by posture and which communicates with the intracochlear fluids via the cochlear and vestibular aqueducts, can be summarised in general as follows. The labyrinthine pressure change is probably mainly caused by the change in hydrostatic pressure in the CSF due to gravity. The CSF system may be represented by a spherical reservoir on the top of a fluid column. The pressure change induced by changes in posture may thus be considered proportional to the vertical height through which the head moves, taking the sitting position as being the approximate reference posture. The CSF pressure is also significantly dependent upon the fact that it is effectively contained within an elastic reservoir; and on venous pressure which is always greater than CSF pressure and can be transmitted to the CSF via the elastically walled veins. Although the CSF hydrostatic pressure change caused by changes in posture is almost instantaneous, the rate of drainage of the CSF is altered and the new pressure equilibrium takes about 15 and 30 minutes to be reached for most posture changes. The exception to this occurs when the movement is to the head-up position, when the pressure change in the CSF seems to take place within a few seconds. This is thought to be due to the play of the vascular reflexes (Bedford 1958, 1959).

Following the above argument in the case of the results of the present experiment leads to the following conclusions. On moving to the recumbent position from the sitting position, the CSF pressure will have reached its new equilibrium value after 20 minutes. On then moving to the sitting position it will return to its original value almost immediately and stay there. On moving from the sitting position to one of the three angles, the CSF pressure will reach a certain value after 20 minutes, dependent upon the posture. The perilymphatic pressure changes which were indirectly measured in this investigation generally agree with this time-table of events.

Carlborg's work on the cat (1981) indicated that perilymphatic pressure is directly proportional to the CSF pressure for changes occurring over more than a second or so. The current experiment shows that, despite cochlear aqueduct patency in humans (considered as a group) being less certain, changes in the perilymphatic pressure appear to reflect those of the CSF quite closely.

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The actual magnitude of the CSF hydrostatic pressure increases following changes in posture will be proportional to h(1-cos(A)). Here A is the angle with respect to the vertical through which the body has moved, and h is the equivalent height of the spinal column taking into account the reduction due to vascular and meningeal aspects. The equivalent height of the spinal column can be estimated by equating the hydrostatic pressure within the Cistern Magna to that of the cochlea. In this case, according to Loman (1934), the pressure is in the range between 40 to -85 mm saline with the subject in a sitting postion. If the pressure at the cochlea level is therefore nominally taken as -20 mm saline in the sitting position, and that in the recumbent position nominally as 150 mm saline (Davson,1970), the difference between them may be estimated as 170 mm saline. Consequently the change in CSF pressure at the cochlea on moving from the sitting position to the three angles, 30°, 60° and 90° may be calculated as 23 mm, 85 mm and 170 mm saline respectively.

The results of the present experiment show that these estimated changes in CSF pressure are reflected to a large extent in the perilymph, as determined by measurements of the TMD response waveforms in terms of the parameters ΔVm and ΔVi. Even the very small pressure change of 23 mm saline due to movement from the upright posture through 30° could be detected by the measurement procedure as a significant change in a group of subjects. In this case the mean change in the parameter ΔVi was 52 nl, as shown in Table 6.5.

It is possible to calculate the change in the lateral displacement of the head of the stapes that corresponds to this very small pressure change from the theoretical models of stapes motion discussed in Chapter 3. Taking the mean stapedial footplate area to be $3.2 \times 10^{-6} m^2$ (Wever and Lawrence, 1954) and a mean footplate/TM volume displacement ratio of 1:10 (Ivarsson and Pedersen, 1977, and Densert et al, 1977), the lateral displacement of the head of the stapes is calculated to be approximately $1.6 \times 10^{-6} m$. From the relationships between stapes displacement and perilymphatic pressure calculated from the model of Marchbanks and Martin (1984a) shown in Figure 3.5, and the similar relationships deduced by Tweed (1985) shown in Figure 3.7, the changes in the stapes lateral displacement per change in perilymphatic pressure may be estimated as approximately 0.069 and $0.055 \times 10^{-6} m$ per mm saline respectively. Taking the mean of these two values and the stapes displacement of $1.6 \times 10^{-6} m$ yields a calculated equivalent change in pressure of 27 mm saline. This compares remarkably favourably with the CSF pressure change of 23 mm saline deduced above from the experimental results.

The errors involved in the assumptions upon which these pressure estimates are based are large, although this is perhaps not reflected in the very small difference between the results of the two approaches. One possible source of error is the fact that the experimentally determined change in ΔVi with posture could be a somewhat conservative measure of the actual volume change. This is because the mean value of ΔVi used included a number of zero values, due either to ears with non inward-going reflexes or perhaps ears with labyrinthine pressures which do not directly reflect the CSF pressure change due to sealed cochlear aqueducts.

Nevertheless the results strongly suggest that, in the age group tested, most subjects show a direct communication between the CSF and the perilymph. Considering that corresponding changes in perilymph pressure occur within the first five minutes of a change in CSF pressure, the most likely route for this communication between fluids is the cochlear aqueduct. Given a larger population of several different age groups, it would be interesting to see whether the mean change in ΔVi with posture would reflect the disappearance of the patency of the cochlear aqueduct with age reported by Wlodyka (1978), as discussed in section 2.1.3.

In at least three of the 24 subjects tested (ie. 12%), there seemed to be no correlation between the changes in ΔVm and ΔVi and posture. This would indicate that in these subjects there is no communication between the perilymph and the CSF, in other words the cochlear aqueduct is not patent. For the age range of the subjects tested, this frequency of occurrence for non-patent aqueduct is in agreement with experimental results of Wlodyka (1978). Using a direct test of cochlear aqueduct patency on human temporal bone preparations, Wlodyka found an 18% incidence of non-patency, which is close to the present estimate.

The CSF pressure is known to equilibrate within a few seconds when subjects are returned to the sitting position from the recumbent position (Bedford 1958, 1959). The fact that there are obvious positive trends in the values of both ΔVm and ΔVi shown in Figure 6.1 over the 20 minutes following the posture manoeuvre, although not statistically significant, does suggest that there could be some damping of fluid flow through the cochlear aqueduct. This needs further investigation with a larger sample of experimental subjects.

Another important result from this experiment is that the changes in ΔVm and ΔVi resulting from posture manuevres seem to be independent of their original values in the sitting position. That is they appear to independent of whether the TM response

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configuration is inward, outward or biphasic. The change in maximum inward TM volume displacement (ΔVi) appears to be the more sensitive parameter as the standard deviations of this measure are smaller than for ΔVm. Unfortunately, however, as a descriptor of perilymphatic pressure change it suffers from the disadvantage that it cannot be measured in subjects with entirely outward-going reflex TM displacement configurations. This configuration occurs in approximately 30% of normal subjects.

The electromechanical model of Brask (1978) and the mathematical models of Marchbanks and Martin (1984a) and Tweed (1985) all predict that an increase in perilymphatic pressure will favour a more inward-going reflex TM displacement. The current study provides empirical evidence to support this hypothesis. It therefore also provides additional experimental support for the validity of clinical measures of abnormally high intra-cochlear fluid pressure which are based on these models (Marchbanks and Martin, 1983).

The ability of the TMD measurement technique to gauge abnormally high fluid pressure, combined with the ability to detect small changes in perilymphatic pressure and cochlear aqueduct patency, is likely to prove of great clinical significance in the near future. The time-course of labyrinthine fluid related disorders, such as the various forms of Meniere's Syndrome, are probably closely related to these factors, as is the manner in which posture and CSF pressure effect the labyrinth, as discussed in Chapter 2. In particular, if endolymphatic hydrops is present in a patient and his cochlear aqueduct is patent, episodes of rapid and large changes in CSF pressure (possibly induced by changes in posture) will probably be intimately related to the time-course of the disorder. Cases of extreme CSF pressure changes may even cause rupture of Reissner's membrane.

Conversely if the cochlear aqueduct is sealed, the cochlear is buffered form the extremes of pressure which occur in the CSF system and therefore the time-course of any labyrinthine pathology will probably be more closely related to the lesser pressure changes in the cochlear fluids themselves.

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CHAPTER 8

CONCLUSIONS

The experimental work described in this report has shown that an estimated pressure change of only 30 mm saline in the perilymph fluid can be detected by the TMD measurement system in a group of subjects as a change in both the mean volume displacement and the maximum inward volume displacement of the tympanic membrane during contraction of the stapedius muscle. If the reflex TM response configuration has an inward component then it seems possible that an even smaller perilymphatic pressure change of approximately 15 mm saline can be detected.

With the majority of ears the change in perilymphatic pressure, as measured in terms of the reflex TMD, faithfully reflects the expected and well documented changes in CSF pressure brought about by controlled changes of posture. In these cases, a patent cochlear aqueduct would seem to be the most probable route for this pressure transfer from the CSF to the perilymph fluid to take. There are noteable exceptions to this, however, in that at least 12% of the ears tested showed no change in perilymphatic pressure with a change in CSF pressure. In this proportion of ears the cochlear aqueduct would not appear to be patent. This proportion of non-patency is probably particular to the age range of the subjects tested, 18 to 30 years, and according to histological studies will increase with age.

The experiment has shown that measurements of stapedial reflex induced displacement of the TM may be used to provide a sensitive measure of changes in perilymphatic pressure, and these results are in general agreement with previous mathematical models. The measurement technique therefore provides a means of detecting high intra-cochlear fluid pressures in patients with hydrops. This, together with the ability to detect cochlear aqueduct patency, is of great importance in the investigation of inner ear disorders which effect the labyrinthine fluid physiology. In particular the measurement technique may have a significant bearing on the investigation of the time-course of certain forms of paroxys mal vertigo such as Meniere's Syndrome.

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APPENDIX

POLYNOMIAL REGRESSION ANALYSES OF CHANGES IN TYMPANIC
MEMBRANE DISPLACEMENT WITH ANGLE AND TIME

TABLE Al   Summary of Analysis of Variance Due to Polynomial
Regression of the Change in Mean Tympanic Membrane Displacement,
ΔVm, with Angle and Time, Using the Body Angle as Predictor.

Source of Variance		DF	SS	MS
Between-Subject		23	1836033	79828
Angle		2	984388	492194
	Linear	1	885200	885200
	Quadratic	1	99170	99170
Time		3	93847	31282
Angle x Time		6	42385	7064
	Linear	3	19890	6631
	Quadratic	3	22490	7498
Betwen-Subject x Angle		46	3128000	68000
	Linear	23	1218000	52940
	Quadratic	23	1910000	83050
Between-Subject x Time		69	591900	8578
Between-Subject x Angle				
	xTime	138	763400	5532
	Linear	69	383800	5562
	Quadratic	69	379600	5502
Total		287	7439693	

(i) The linear coefficient for the mean of the four time
intervals is significantly different from zero if:

$$885200/52940 \; > \; F_{1,23}(0.95)$$

which is the case and the coefficient is therefore significant.
(ii) The linear coefficients for the four time intervals are
significantly different from each other if:

$$6631/5562 \; > \; F_{3,69}(0.95)$$

which is not the case, and thus they are not significantly
different from each other.

TABLE A2 Summary of Analysis of Variance Due to Polynomial Regression of the Change in Maximum Inward Tympanic Membrane Displacement, ΔV_i, with Angle and Time, Using the Body Angle as Predictor.

Source of Variance		DF	SS	MS
Between-Subject		23	2020847	87863
Angle		2	330554	165277
	Linear	1	292400	292400
	Quadratic	1	38100	38100
Time		3	52305	17435
Angle x Time		6	22197	3699
	Linear	3	11070	3691
	Quadratic	3	11120	3708
Betwen-Subject x Angle		46	1474000	32050
	Linear	23	798000	34690
	Quadratic	23	676300	29400
Between-Subject x Time		69	354100	5131
Between-Subject x Angle				
	xTime	138	679700	4925
	Linear	69	249400	3614
	Quadratic	69	430300	6236
Total		287	4933913	

(i) The linear coefficient for the mean of the four time intervals is significantly different from zero if:

$$292400/34690 > F_{1,23}(0.95)$$

which is the case and the coefficient is therefore significant.

(ii) The linear coefficients for the four time intervals are significantly different from each other if:

$$3691/3614 > F_{3,69}(0.95)$$

which is not the case, and thus they are not significantly different from each other.

TABLE A3 Summary of Analysis of Variance Due to Polynomial Regression of the Mean Tympanic Membrane Displacement, ΔVm, with Angle and Time, Using the Time Interval as Predictor.

Source of Variance		DF	SS	MS
Between-Subject		23	1836033	79828
Angle		2	984388	492194
Time		3	93847	31282
	Linear	1	48441	48441
	Quadratic	1	35867	35867
	Cubic	1	9538	9538
Angle x Time		6	42385	7064
	Linear	2	11546	5773
	Quadratic	2	20724	10360
	Cubic	2	10115	5058
Betwen-Subject x Angle		46	3128000	68000
Between-Subject x Time		69	591900	8578
	Linear	23	248700	10810
	Quadratic	23	224500	9761
	Cubic	23	118700	5162
Between-Subject x Angle xTime		138	763400	5532
	Linear	46	341800	7430
	Quadratic	46	234600	5100
	Cubic	46	187000	4065
Total		287	7439693	

(i) The linear coefficient for the mean of the three angles is significantly different from zero if:

$$48441/10810 > F_{1,23}(0.95)$$

which is the case and the coefficient is therefore significant.

(ii) The quadratic coefficient for the mean of the three angles is significantly different from zero if:

$$35867/9761 > F_{1,23}(0.95)$$

which is not the case, and thus it is not significant.

TABLE A4 Summary of Analysis of Variance Due to Polynomial Regression of the Maximum Inward Tympanic Membrane Displacement, ∆Vi, with Angle and Time, Using the Time Interval as Predictor.

Source of Variance		DF	SS	MS
Between-Subject		23	2020847	87863
Angle		2	330554	165277
Time		3	52305	17435
	Linear	1	30415	30415
	Quadratic	1	2427	2427
	Cubic	1	19463	19463
Angle x Time		6	22197	3699
	Linear	2	13021	6510
	Quadratic	2	8476	4238
	Cubic	2	700	350
Between-Subject x Angle		46	1474000	32050
Between-Subject x Time		69	354100	5131
	Linear	23	107900	4692
	Quadratic	23	152700	6641
	Cubic	23	93410	4062
Between-Subject x Angle				
	xTime	138	679700	4925
	Linear	46	283700	6167
	Quadratic	46	236200	5135
	Cubic	46	159800	3474
Total		287	4933913	

(i) The linear coefficient for the mean of the three angles is significantly different from zero if:

$$30415/4692 > F_{1,23}(0.95)$$

which is the case and the coefficient is therefore significant.

(ii) The quadratic coefficient for the mean of the three angles is significantly different from zero if:

$$2427/6641 > F_{1,23}(0.95)$$

which is not the case, and thus it is not significant.

It can be seen from Tables A1 and A2 that for both ΔVm and ΔVi averaged over 4 time intervals, the linear regression coefficients were significantly different from zero (5% of F-distribution). None of the linear coefficients for the separate time intervals were significantly different from each other however. Unfortunately, since there were only three values for the predictor in this case, the significance of the quadratic coefficients could not be estimated.

In Tables A3 and A4 the linear regression coefficients for both ΔVm and ΔVi averaged over the three angles were significantly different from zero. Again the linear coefficients for the separate angles were not significantly different from each other for ΔVm and were only of borderline significance for ΔVi. With four values for the predictor the significance of the quadratic coefficients could be estimated in this case, but they were found not to be significant for either ΔVm or ΔVi.