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The incudo-malleal joint

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Introduction

THE primary function of the middle ear is to transmit vibrations in air to the perilymph of the cochlea.

The acoustic impedance matching system of the middle ear, achieved by the hydraulic transformer mechanism and the lever action of the ossicles, represents the acoustic component of the middle ear.

The second function of the middle ear, too often overlooked, is the 'buffering' matching system of the middle ear, determined by its mechanical components. Even with a variation in the order of magnitude of $10^{\sqrt{4}}$, both matching systems are too often mixed and confused.

The aim of this paper is to establish clearly the essential role played by the mechanical components of the middle ear, of which the incudo-malleal articulation appears to be the main part.

Since Helmholtz's basic publication 'The sensation of Tone', published in 1863, our knowledge of the anatomy and physiology of the middle ear has remained relatively unchanged and little has been added to the original information provided by such authors as Politzer (1884), Toynbee (1865), von Békésy (1960), and Wever and Lawrence (1954).

Surprisingly, many errors and imperfections have appeared systematically in the literature over the years; even more surprisingly anatomical–physiological descriptions, which were previously accurate, have been disregarded.

This is particularly true for some parts of the middle ear: for example, the incudo-malleal joint which, though thoroughly studied by Helmholtz, Pappenheim, Kobrak and others, has generally been disregarded in modern literature.

Authors such as Dahmann (1930) and Frank (1923) suggested a functional role for this articulation, in contrast to Bárány (1910) and von Békésy (1939) who regarded the incudo-malleal block as a rigid body, without acknowledging its articular movement. Consequently this latter opinion has been generally accepted.

This paper attempts to bring together some old, and more recent, information concerning the anatomy and physiology of this articulation.

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Material and Methods

Source of information

Since 1964 more than 3,000 human temporal bones and an even greater number of tympano-ossicular sets, including those with pathology and congenital malformations, have been studied in our temporal bone bank.

Surgery performed under the most modern conditions of anaesthesia and haemostasis has also been a useful source of information, especially in the surgery of otosclerosis and in homograft surgery.

Light- and electron-microscopic studies have also been useful in providing a complementary source of information.

Audiology, including tympanometry, has been a source of data of incomparable value, because the information thus provided has been collected on living patients and has been clinically verifiable.

Last but not least, information derived from the use of modern techniques of photography, cinematography, holography, stroboscopy and TV recordings has been particularly helpful for comparative studies between live and dead material.

Main premises

The main premise in this study has been that, in Nature, no single anatomical structure is useless and that the function of any organ may be deduced from its anatomical particularities. For instance:

1. Tendons and ligaments always function in accordance with the laws of mechanics, though some particular and well-defined anatomical structures imply well-defined types of motion and exclude others.
2. Ligaments are built with variable tensional strengths, according to their morphological and physiological characteristics.
3. The very particular structural shape of the incudo-malleal articulation cannot be considered to be physiologically insignificant.

Causes of errors

The main difficulties in understanding correct function and in interpreting errors which may arise during animal experiments, depend upon the method of anaesthesia used and on its effect on physiological parameters. Most studies of human material have been made on dead material: the effect of 'rigor mortis' (von Békésy, 1939) is one of the elements to be considered and these include modifications in stiffness or tensional strength produced by fixation or preservation techniques. Live human experiments on healthy ears, in normal physiological conditions, have not yet been done and hypotheses are therefore still necessary.

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Definitions

The possibility of three-dimensional motion in the tympano-ossicular chain has been studied by examining serial sections through the horizontal, frontal and sagittal planes (Fig. 1a, b, c).

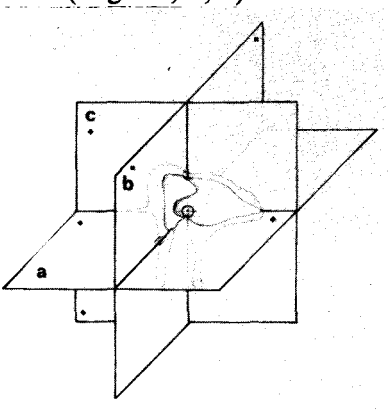


FIG. 1

The three dimensional planes:
(a) horizontal; (b) frontal; (c) sagittal.

The horizontal plane (a) passes through the anterior malleal process and the centre of gravity of the incudo-malleal block, and so determines the axis of rotation of that mass.

The frontal plane (b), perpendicular to the plane (a), also passes through the centre of gravity of the incudo-malleal block.

The sagittal plane (c) passes through the axis of rotation of the incudo-malleal system; it lies perpendicular to (a) and (b).

A second definition should be made regarding the *anatomical transverse* axis of the whole tympano-ossicular system in the middle ear (Fig. 2). Taking the horizontal plane, a perpendicular (AB) is dropped to the

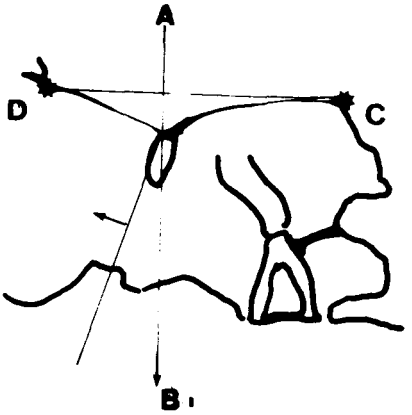


FIG. 2

The anatomical transverse axis.

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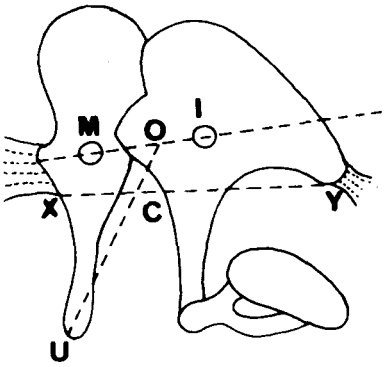


FIG. 3

The centre of gravity (O) and the axis of rotation (M.I.), after von Békésy (from Kirikae).

sagittal plane determined by the footplate. This perpendicular line (AB) makes an angle of 5° with the projection of the longitudinal axis of the tensor tympani tendon on the horizontal plane.

Both the malleus and the incus have their own *centres of gravity,* represented by M and I (Fig. 3). O is the centre of gravity of the whole incudo-malleal mass. This divides the line M–I in the ratio:

$$MO/IO = 27/23 \text{ (Kirikae, 1959).}$$

Assuming (after Kirikae, 1959) that the centre of gravity of the tympanic membrane alone is at the umbo (u), and taking the total mass of the tympano-ossicular system into consideration, it is found that the centre of gravity of the tympano-ossicular system is at (C), on the line joining (U) to (O), so that CU : CO = 50 : 14. XY is regarded as the classic axis of the tympano-ossicular system (Fig. 3).

According to our research, the centre of gravity of the incudo-malleal block, reported by Kirikae as (O), corresponds exactly with the articular structure described hereafter as the 'malleal ball', which is part of the apparent ball-and-socket articulation of the incudo-malleal joint.

This anatomical point lies within the head of the malleus near the tympanic membrane, ±2 mm. above the centre of the fixation point of the tensor tympani, 300 μ from the anterior crest and 1·5 mm. above the lateral process.

As shown in the present study, the only invariable *axis of rotation* of the ossicular incudo-malleal block is determined by a line passing through the centre of gravity of the malleus, M, which joins the anterior extremity of the long process of the malleus and the 'malleal ball', which corresponds to (O).

The posterior half of the rotation axis, or the incudal rotation axis, is thus variable, having only one unvariable fixation point, the 'socket' of the 'malleal ball'; the posterior fixation point of the incus is variable. This axis

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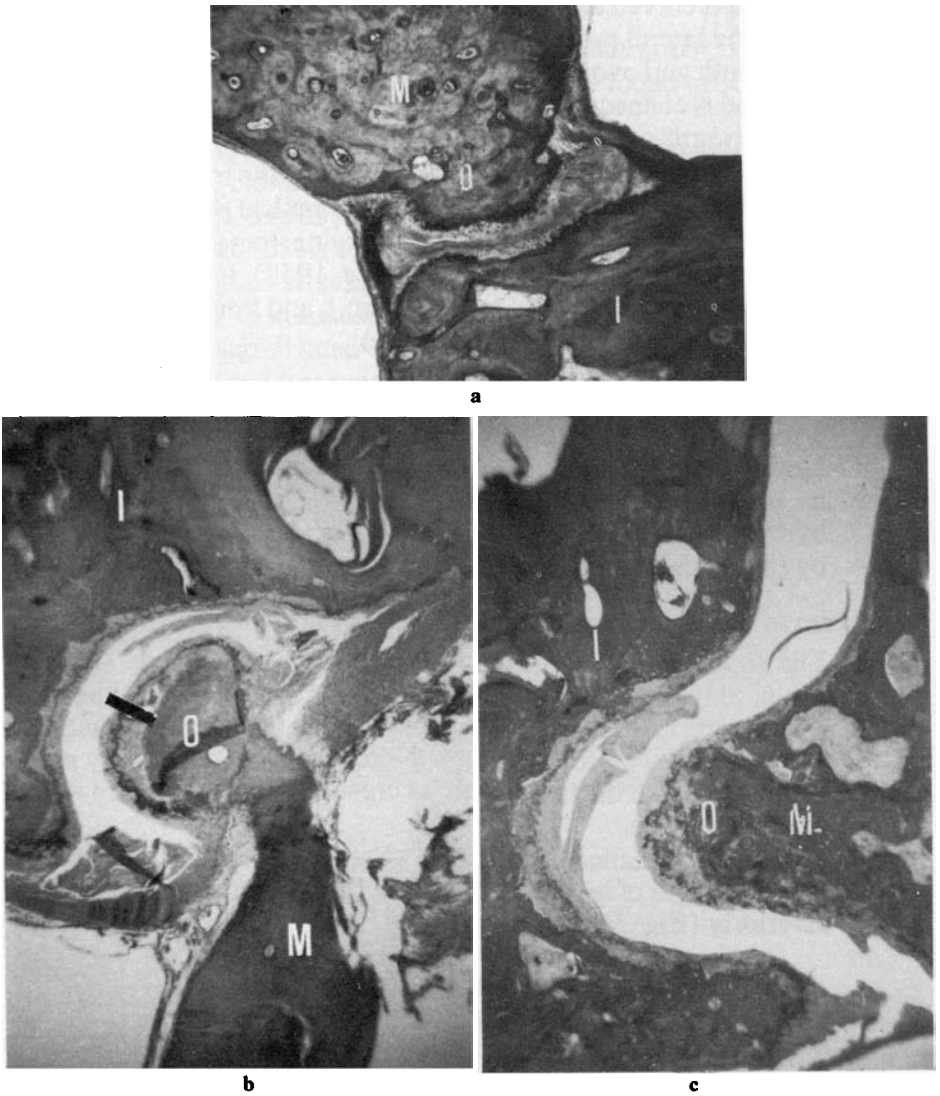


FIG. 4

The incudo-malleal joint showing a ball-and-socket type of joint.
(a) in plane a; (b) in plane b; (c) in plane c.

of rotation does not correspond to the classically recognized rotation axis, as defined by Békésy (1959) (Fig. 4a, b, c).

Anatomy

The malleus

The malleus can be compared to a long bone, and is composed of a head, a handle, a neck and an anterior process.

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The handle is curved and ends inferiorly in a small spatula, the umbo, superiorly in the lateral process. The head lies in the attic and its anterior surface is smooth and ovoid. Posteriorly two articular facets join it to the incus. The head is connected to the handle by the neck of the malleus with an obliquity inwards and backwards. On its lateral aspect it is crossed by the lateral malleal transverse crest, and medially by the transverse groove of the chorda tympani. The base of the anterior malleal process lies on its anterior aspect. This ossicle weighs 23 mg., varying from (20·15±0·6 mg.) at birth to (24·9±0·7 mg.) in the adult (Kirikae, 1959). Its length from the umbo to the top of the head is (8·00±0·08 mm.); and from the head to the lateral process it measures (5·00±0·4 mm.).

Ligaments and tendons

The malleus is fixed in four ways:

1. by the static ligamentous points of attachment
2. by the pseudo-articular joint
3. by the articular capsule
4. by the tendinous points of fixation.

THE STATIC LIGAMENTOUS POINTS OF ATTACHMENT ARE:

1. The superior malleal ligament, which is short. Its role is purely static, in that it holds the whole ossicular system within the attic.
2. The lateral malleolar ligament, which lies in continuity with the anterior malleolar fold. This ligament is stretched medially and is strongly fixed to the lateral malleal crest, to form the medial wall of Prussak's space.
3. The anterior malleal ligament is short and very strong, with an average length of less than 1·5 mm. It fixes the malleus very firmly anteriorly (Fig. 5).



FIG. 5
The anterior malleal ligament.

4. The posterior malleolar fold is thin but strong, with an average length of 2·7 mm. It binds the pre-tympanic spine on the base of the lateral process of the malleus and stabilizes the malleus in the sagittal plane. It must not be confused with the stria tympanica posterior, which belongs to the tympanic membrane.

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The tympanic membrane

In a recent study by Ars (1977), carried out in our department, the main data about the tympanic membrane were found to correspond with those of Kirikae (1959).

These are: the horizontal diameter of the tympanic membrane is (7·9±0·8 mm.), the vertical diameter (7·5±0·5 mm.). Its surface area is (55·4±4·5 mm.^{2}), and its thickness varies from 0·06 mm. to 0·9 mm. at the centre. The membrane is cone-shaped and it may also be considered as a fixating ligamentous structure.

Its structure is composed of three groups of fibres: radial fibres; circular fibres, sub-divided by Kirikae into concentrically circular and parabolic fibres; and transverse fibres, running horizontally in the inferior quadrant. The tympanic membrane is firmly attached all round the tympanic ring by the fibrous annular ligament, but its attachment to the manubrium is variable (Fig. 6a, b, c).

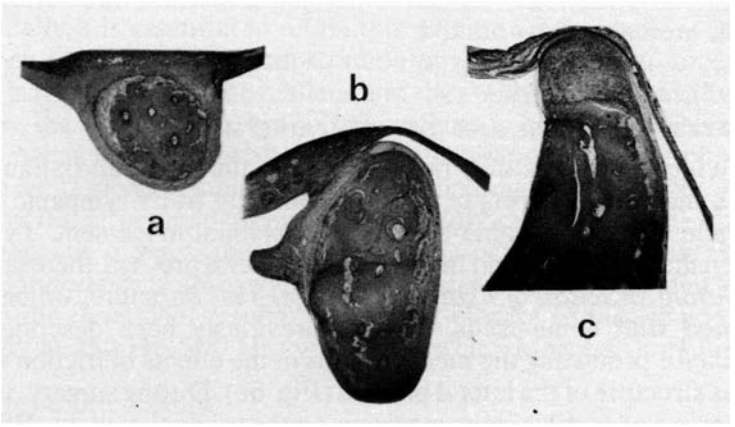


FIG. 6

Tympanic attachment to the manubrium a, b, c.

At the umbo the tympanic membrane, which is in continuity with the strongly attached periosteum of the spatula-shaped end of the malleus, forms at this point one of the strongest points of fixation of the tympanic membrane to the manubrium over an area 7/10 mm. wide. This structure is obvious when one has to dissect remnants of a drum from the manubrium during surgery, or when preparing a tympanic homograft (Fig. 6a).

All along the lateral crest of the manubrium, over a length of 4 mm., the fixation points of the tympanic membrane correspond to a very narrow line of less than 100 microns thick. Characteristically the fibrous attachment is well vascularized but is strong on the posterior aspect only, the anterior aspect being more lightly structured. From this it may be assumed that there is only passive motion in the anterior part of the

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tympanic membrane, with little or no traction or pulling action, and an active and strong pulling action in the posterior part of the tympanic membrane (Fig. 6c).

At the lateral extremity of the lateral process of the malleus, the fixation of the drum is so constructed that we have classified it as a pseudo-articular joint (Fig. 6c).

The attachment of the tympanic membrane to the manubrium is unique; it produces a firm attachment between a vibrating membrane and a rigid ossicle. So far no surgical technique has been able to copy or to restore this structure in the long term, and the preservation of this pecularity is one of the main advantages to be gained by using tympano-ossicular homografts in reconstructive ear surgery.

THE PSEUDO-ARTICULAR JOINT

This term has been chosen because it behaves differently from other ligamentous structures, for the other joints permit three-dimensional motion, no matter how limited.

THE LATERAL PROCESS AND THE TYMPANIC MEMBRANE

The lateral process may be compared to the top of an Indian tent. It binds a membrane, strongly fixed peripherally in its tympanic ring, to an ossicle which is capable of three dimensional movement. Typically, between the membrane and the bone of the lateral process, there is a *small articulating structure of hyaline cartilage.* This structure, which can be compared with a meniscus, has not previously been described; it is essential for protecting the membrane from the effects of friction with the osseous structure of the lateral process (Fig. 6c). During surgery, it is wise to preserve this cartilaginous meniscus on the original malleus. When it is necessary to remove it together with the remnants of the drum, it should be replaced by the one included in the tympanic homograft. Absence of this cartilage leads to a local necrosis in the implanted drum, at this point.

THE JOINT OF THE ANTERIOR MALLEAL PROCESS

This joint is perhaps the most important of all, but it has been almost totally disregarded. Not only does it lie upon, but it is also the true axis of the whole ossicular system.

The anterior malleal process is attached to the anterior petro-tympanic fissure by a surrounding fibrous structure. This attachment may be compared with an articulation because it holds the malleus in its normal anatomical and functional position, so allowing a very slight, three-dimensional movement of the malleus. It is related superiorly to the anterior malleal fold, medially to the capsule of the muscle of the tensor tympani, inferiorly to the chorda tympani, and laterally and inferiorly to

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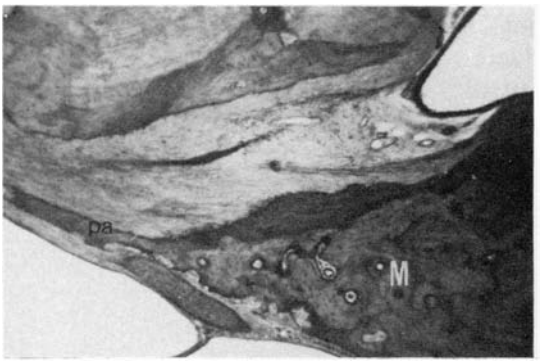


FIG. 7
The anterior malleal process (pa).

the anterior malleal ligament, with which it is often confused (Fig. 7). Its role was stressed by Helmholtz.

Surgically it is essential to retain this structure if the malleus stem is used for an incudo-stapedial substitution prosthesis, or when prosthetic material is fitted between the malleus and the stapes. The primordial role played by the anterior process of the malleus is also demonstrated by tympanometry, for no major alterations in the tympanogram are observed when the incus alone is totally removed. In homograft surgery the ability to preserve this structure determines whether or not to remove the malleus and to replace it by a monobloc tympano-ossicular implant. When possible, preference is always given to the preservation of the joint for, as shown in the functional results, if it is not, closure of the air-bone gap (especially at 250 Hz–500 Hz) will never occur (Marquet *et al.*, 1975).

THE ARTICULAR CAPSULE

The malleus is bound to the incus by its articular ligament, which forms the articular capsule. This capsule has a variable thickness which corresponds to the dynamic movements of the articulation.

THE TENDINOUS FIXATION POINTS

The attachment of the tensor tympani is centered on the neck of the malleus below the base of the anterior process, 3·5 mm. from the umbo. Its area of fixation is 1·6 mm.^{2}, situated on the anterior face of the triangular-shaped section of the malleus (Fig. 8).

An appreciation of this attachment is essential to an understanding of the medialward pull exerted by the tensor tympani, which also produces a slight anterior and medial rotation of the malleus neck on its vertical axis, during contraction of the muscle. The frontal plane, passing by the longitudinal axis of the manubrium, forms an angle of approximately 3 degrees with the longitudinal axis of the malleus neck; the resulting movement of the manubrium is a slight torsion on the sagittal axis.

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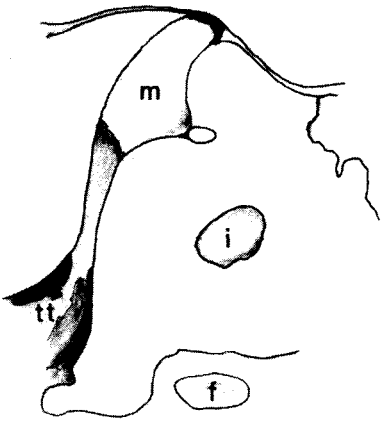


FIG. 8
The tensor tympani (tt) and its attachment to the malleus.

The incus

The general appearance of this ossicle is like that of a bow, prolonged by its short limb, and with its long limb ending at the lenticular process.

The body of the incus lies in the attic recess. It has three facets: the external one faces laterally; the internal one medially; and the anterior elliptical, concave articulatory facet joins with the complementarily shaped articular facet of the malleus.

The ossicle is light, weighing (20·58±0·7 mg.) at birth, (27·39±1·03 mg.) in the adult. According to Kirikae, all dimensions of the incus are very constant. They are: from the highest part of the incus to the tip of the long process (6·79±0·07 mm.); from the tip of the short process to the near edge of the joint (3·83±0·01 mm.).

LIGAMENTS

The superior ligament is a suspensory ligament, which connects the upper part of the body of the incus to the tegmen. Both Kirikae and we ourselves find this ligament to be an inconstant one, varying in both form and appearance. The lateral incudal ligament is very often expandable and frequently confused with the medial and lateral incudal folds, which play a very important role in the pathogenesis of disease in this area, but are of no mechanical significance.

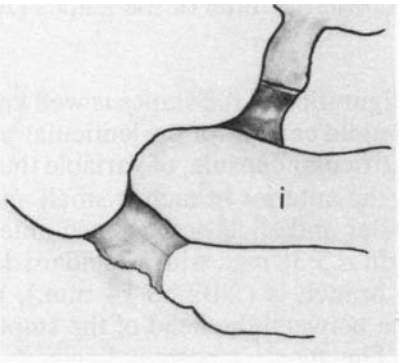
PSEUDO-ARTICULATION

THE POSTERIOR INCUDAL LIGAMENTS

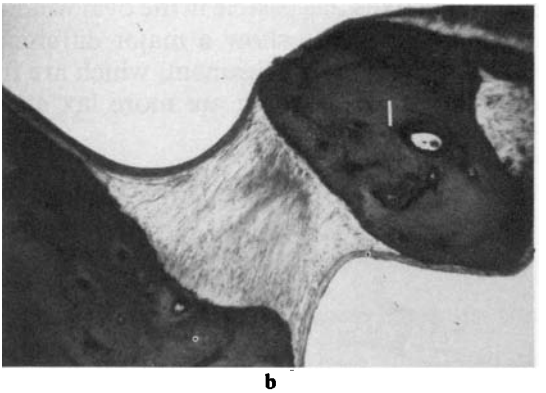
These ligaments, which attach the posterior aspect of the body to the fossa incudis, have often been incorrectly described. Politzer described them correctly, as fish-tailed in shape; so also did Guerrier (1962). The

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posterior extremity of the incus is fixed by two round ligaments: a lateral one (700 $\mu \times 500\ \mu$); and a medial one (400 $\mu \times 500\ \mu$). Each has a different axis. The articular surface of the short process of the incus is fixed slackly in the fossa incudis. Movement at this pseudo-articulation is capable of



a



b

FIG. 9

(a) and (b) The medial and lateral ligaments of the short process of the incus.

being three-dimensional (Fig. 9). The covering mucosal structure may be responsible for its often erroneous description as a posterior ligament attached to the posterior end of the processus brevis.

THE ARTICULAR CAPSULE

The capsule of the incudo-malleal joint forms the anterior attachment of the incus.

The incudo-stapedial joint

This joint is a true diarthrodial articulation, between the lenticular process of the incus and the head of the stapes. Here also the antero-inferior part of the ligament is small and has more laxity than the postero-superior part.

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The tendinous fixation points

The position of attachment of the stapedius tendon is variable. In 6 per cent of persons, it is attached to the lenticular process itself; in 29 per cent to the capsular ligament; in 62 per cent, to the head of the stapes; and only in 3 per cent, to the posterior crus of the stapes (Ars, 1977).

The stapes

The general configuration of the stapes is well known. The head of the stapes has a small glenoid cavity, for the lenticular process of the incus. It is surrounded by an articular capsule, of variable thickness. The stapedial arch is asymmetric: the anterior branch is small and thick; the posterior branch is much smaller and slightly narrowed anteriorly.

The average weight is 3·38 mg., with a standard deviation of ±0·48 mg. The height of each branch is (2·02±0·14 mm.), according to Kirikae (1959). The distance between the head of the stapes and its footplate is (3·29±0·15 mm.). The most important ligament of the stapes is the annular ligament, which fixes this ossicle in the oval window. Histological studies of the annular ligaments show a major difference between the posterior and superior parts of this ligament, which are firmly fixed, and the anterior and inferior parts, which are more lax and permit greater freedom and movement (Fig. 10a, b).

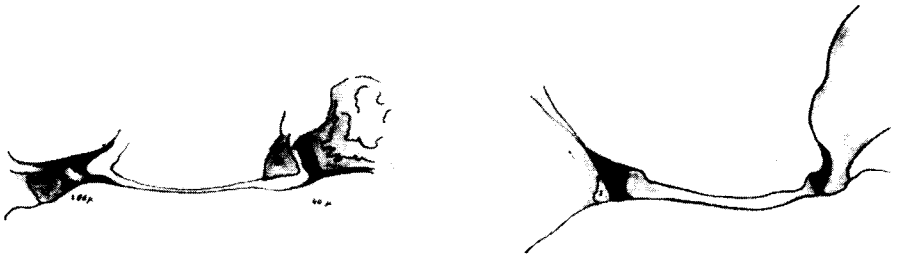


FIG. 10

The annular ligament:
(a) anterior-posterior section; (b) supero-inferior section.

The Incudo-malleal Articulation

This articulation is a true diarthrodial joint, composed of two articular facets, with a small 'ball' on the malleal side, corresponding to a homologue facet and a cap on the incudal side.

All the articular surfaces are covered by a layer of hyaline cartilage and contain very thin fibrous structures similar to intra-articular ligaments. Posteriorly they are prolonged into a smooth cuneiform cartilaginous meniscus, which was studied by Pappenheim in 1840 and described by Politzer (1884).

Presumably the joint contains synovial fluid.

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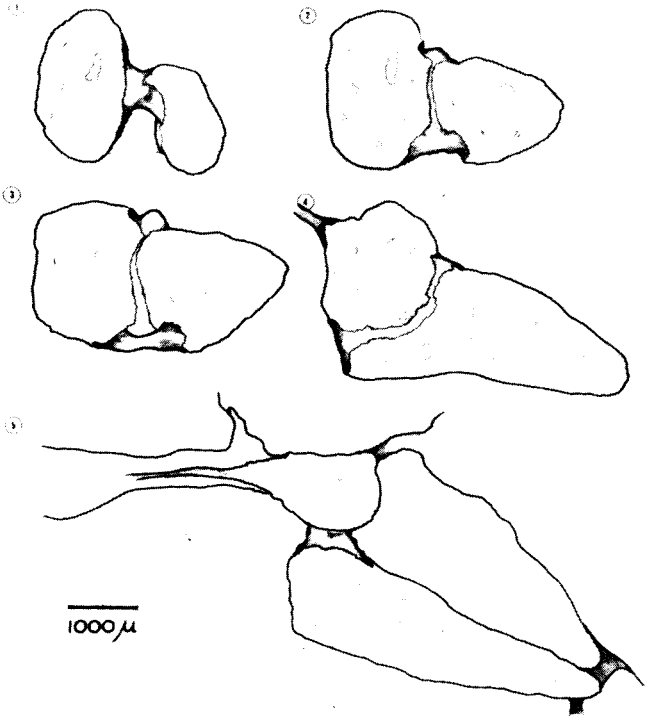


FIG. 11
Horizontal cross-sections of the incudo-malleal joint.

The orientation of the articular facets permits three-dimensional movement.

To understand the structure of the incudo-malleal joint, we have made serial cross-sections of this structure in three different dimensional planes.

Horizontal serial sections from above downwards (Fig. 11) illustrate the articular configuration in its horizontal plane (a) and show that movement is possible in this plane around the 'ball', as seen in Section 4. This 'ball' should be identified with the centre of gravity of the whole tympano-ossicular system. The articular space widens posteriorly to make an angle estimated at 5 degrees which faces medially (Fig. 12). Laterally the articular joint is held firmly by a small strongly attached ligament, 200 μ thick, about which the joint is hinged. In this same plane the medial aspect of the joint is closed by a similar but stronger ligament, 700 μ wide.

The convex shape of the malleal articular surface begins to appear in the sections and increases progressively in convexity as the lower sections are reached. Below the centre of gravity the articular interfaces become antero-posterior in apposition.

Articular motion in the horizontal plane allows a slight rotation on the

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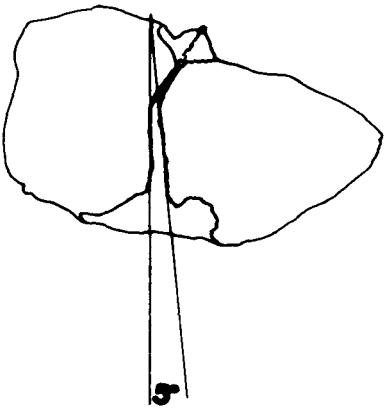


FIG. 12

The 5° angle between malleus and incus.

vertical axis of the malleus head, medially and frontally; and the body of the incus, medially and posteriorly. These movements are produced by the force exerted by the tensor tympani on the malleus (Fig. 15) or, in an accessory way, by a force exerted by the stapedius muscle on the incus.

Serial sections from without inwards show the articular configuration in the sagittal plane (c) and the movement possible around the 'ball' is seen in Section 6 (Fig. 13b).

Both the superior and the inferior articular ligaments are very similar to one another in thickness and presumably in tension. They are generally thin, except medially, where the upper ligament is thicker. In the cadaveric position, the articular surfaces of the malleus and of the incus are parallel to one another and separated by 150 μ. The shape of the malleal articular surface is slightly convex in its lateral half, but where the 'ball' appears, it becomes straighter and finally concave (Fig. 13a, b).

From these serial sections, it may be deduced that a slight rotation of both ossicles may occur on their transverse axes around the 'ball'. These movements are produced by the equivalent of the small frontal vectorial force (f) of the tensor tympani exerted on the malleus, or of the force exerted by the stapedius muscle on the incus or incudo-stapedial joint.

Sections taken from before backwards demonstrate the complexity of the articular configuration in the frontal plane (b), and the degree of movement possible in that plane around the 'ball' is best seen in Section 12 (Fig. 14a, b).

The anterior three-quarters of the articulation may be compared to a hinged knee-joint upside-down; the meniscus lies medially, the 'ball' inferiorly, and the cupula superiorly. In the posterior quarter, the incus may rotate around the central point at the level of the 'ball'. Thus in this plane, one may deduce that the incus, centered on and around the 'ball' of the malleus, may rotate independently on its antero-posterior axis.

From this, it may be deduced that the full activity of this joint includes

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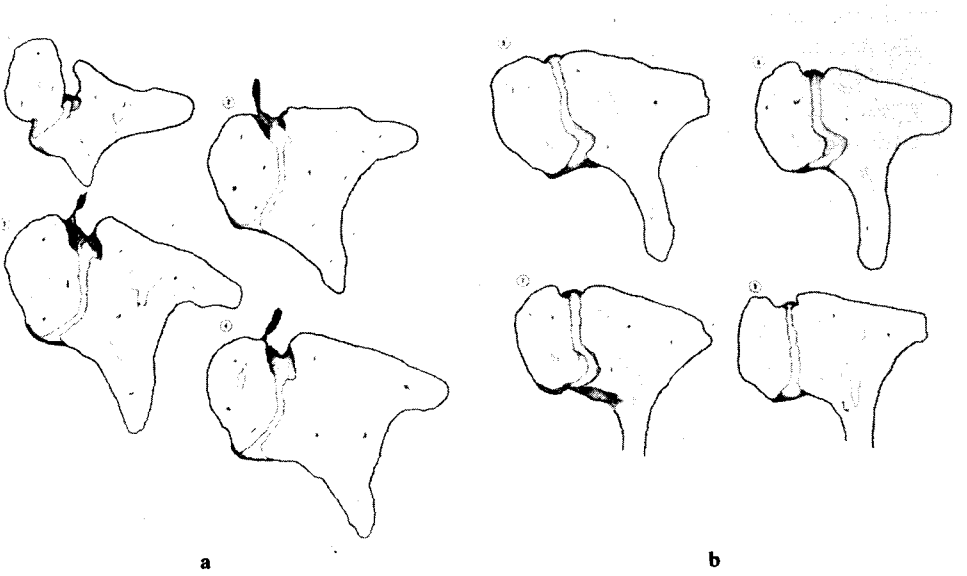


FIG. 13
(a) and (b) Sagittal cross-sections of the incudo-malleal joint.

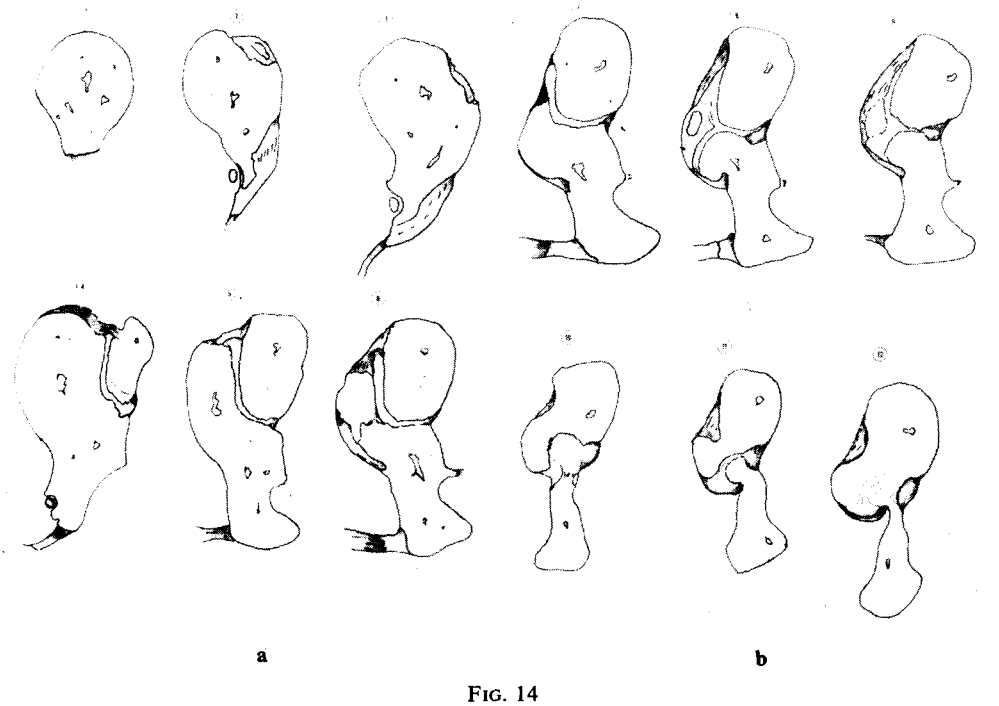


FIG. 14
(a) and (b) Frontal cross-sections of the incudo-malleal joint.

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a flexion of nearly 500 μ of the long process of the incus on the handle of the malleus, in addition to the better-known incudo-malleal 'lever' effect.

Not only may the malleal 'ball' be identified with the true centre of gravity of the incudo-malleal system, but it must also be considered as the true three-dimensional mechanical centre of the articulation.

Movement of the Tympano-ossicular System as Related to its Structure, and Variations which appear after Contraction of the Middle-ear Muscles

As previously mentioned, the attachment of the tendon lies on the anterior face of the neck of the malleus, 2 mm. from the centre of gravity or the 'malleal ball'. In the horizontal plane the moment of this force makes an angle of 5 degrees with the anatomical transverse axis (Fig. 15). Thus,

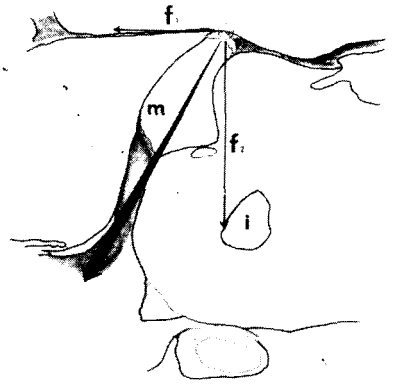


FIG. 15

Contraction Force (F) of the tensor tympani, divided into its components, f1 and f2. The arrows indicate only the direction.

any contraction represented by F may be represented by two vectors, f1 and f2. Considering the lever effect upon the malleus, with its anterior process as fulcrum, the vector f1 would be responsible for a slight shift of the manubrium forwards, and the vector f2 would cause a motion medially. Both forces acting together would result in a slight torsional movement medially and forwards. When the joint surfaces are closed, this motion will be transmitted to the long process and lenticular process of the incus.

Considering the frontal plane b, the articular movement produces a buffering effect between the malleus and the incus. Because the incus can rotate independently, the medial and lateral movements of the lenticular process would be of smaller amplitude than that occurring at the umbo (Fig. 16a, b, c). This elasticity of the joint, for static pressures or other

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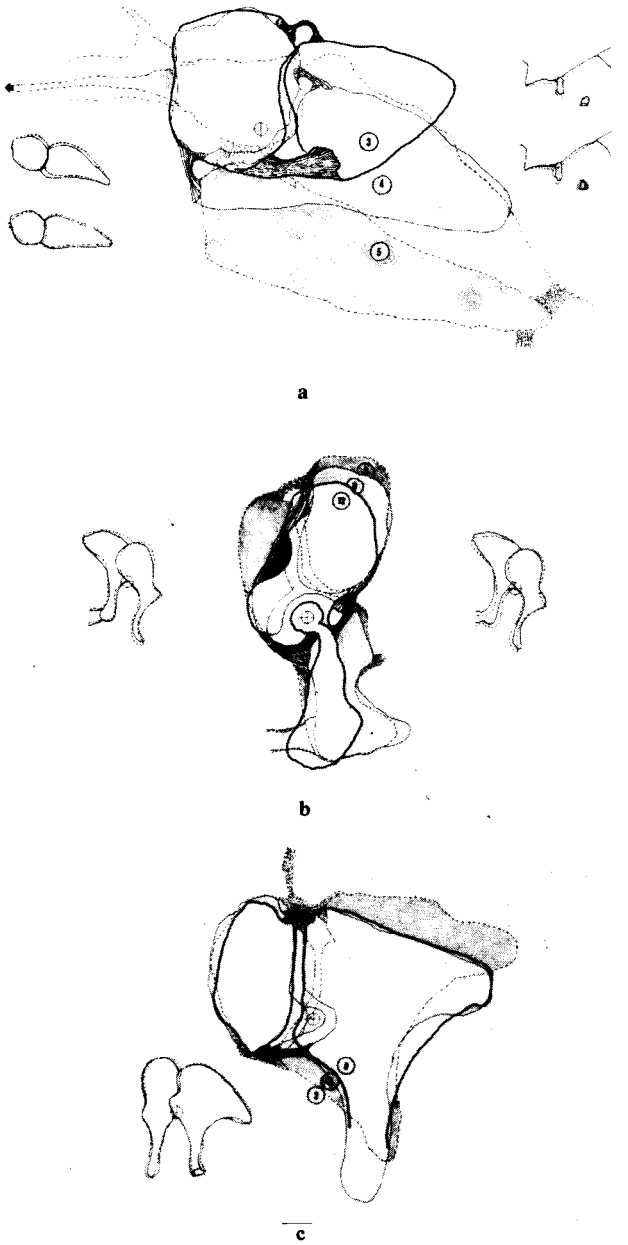


FIG. 16

(a) Horizontal view.
(b) Frontal view. The movements of the incudo-malleal joint, acting as a buffering system to limit displacement of the lenticular process of the incus.
(c) Sagittal view, of the possible buffering movements of the incudo-malleal joint.

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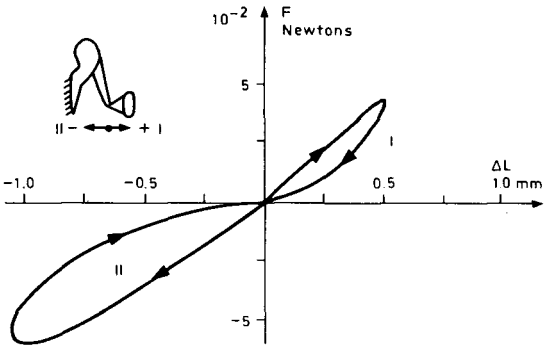


FIG. 17

Holding the malleus fixed, the graph shows the force F needed for both increasing (I) and decreasing (II) distances $\triangle L$ between the malleus and the lentiform (lenticular) process of the incus. The arrows show the sense in which the loops are generated. (*Audiology* (1975), **14**, p. 91, Fig. 6.)

mechanical forces, has already been reported by ourselves and our collaborators (Marquet *et al.*, 1972) (Fig. 17).

Consequently we may deduce that the displacement produced by the action of the tensor tympani, or the opposite lateral displacement of the manubrium (as occurs during a Valsava manoeuvre) will also be buffered and the force exerted will be only a minimal displacement and will be partially transmitted to the lenticular process.

Furthermore a simultaneous action of the stapedius muscle will more readily cancel out this displacement of the lenticular process. The action of the tensor tympani alone, as assessed in the sagittal plane C, would produce a forward movement of both the umbo and the lenticular process. The action of the stapedius muscle alone would pull both backwards, and this accounts for the motion observed with negative pressure, as recorded by the stapedius reflex.

In this plane the vector f1 of the tensor tympani may be considered as the antagonist of the stapedius muscle, and their combined action will markedly reduce the medial displacement of the whole tympano-ossicular system. These considerations concerning the mechanical components of the incudo-malleal joint are not to be separated from the activity of the middle-ear muscles. The tensor tympani muscle, whose activity depends upon either the voluntary or the autonomous nervous system, has a longer latency period and less muscular fatigue than the stapedius muscle.

From direct investigation by electromyography or indirect investigation by tympanometry, we know that the problems connected with the physiology of these muscles are still controversial, the more so as much experimental work has emphasized the physiological differences in various species of mammals, concerning above all the acoustically-elicited tympanic muscle reflexes.

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Our ideas about the activities of the middle-ear muscles assume that contractions of the tensor tympani, whether voluntary or reflex (as in breathing, blowing the nose, swallowing, eructation, deglutition, facial movements or cutaneous stimulations) still occur and accomodate to the displacement, even in the absence of sudden loud sounds.

Contraction of the tensor tympani muscles also occurs after sound stimulation at thresholds which are generally higher than those which are necessary for eliciting a stapedius muscle reflex, except for frequencies lower than 125 Hz; according to our recent experience, these latter are specifically elicited in humans by ipsi—as well as by contra-lateral stimulation at a loudness of 80 db., at 125 Hz.

In contrast to the tensor tympani muscle, the stapedius muscle reacts only reflexly to a sudden increased intensity of loudness, with shorter latency, but with greater fatiguability by muscle adaptation.

Bearing in mind the factors involved in the dynamics of the incudo-malleal articulation, and their complex physiological regulation by the middle-ear muscles, one may predict that the function of these mechanical components (MC) must be to regulate the degree of displacement of the ossicular chain, in order to keep it in a continuous but variable state of stiffness, with regard to the acoustic components (A.C.) which are needed for the transmission of sound vibrations.

Following this hypothesis, thanks to the dynamics of the incudo-malleal articulation and to the action of the middle-ear muscles, the lenticular process of the incus lies in a continuous state of equilibrium with regard to the oval window; and the mechanical motions of the stapes, as shown (Fig. 18a, b, c), are directly related to the possible movements of the incudo-malleal articulation, following planes a, b and c.

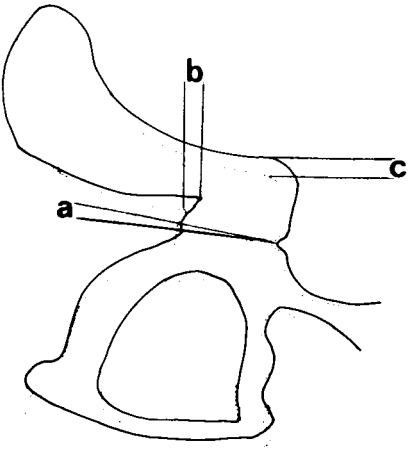


FIG. 18

Buffered mechanical motion of the stapes related to the possible motions of the incudo-malleolar joint in planes a, b and c.

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The spatial position of the footplate would thus be buffered and stabilized according to the mechanical but not to the acoustical amplitudes tolerated by the anatomical and ligamentous structures (Fig. 10a, b). The order of magnitude of this mechanical regulation-matching system is 10^{-4}. In such related and successive positions, the tympano-ossicular system (depending upon laws of acoustic impedance which relate the velocity of the constituent elements to the continuous successive driving forces in the middle ear) would thus work independently of the mechanical component as a true acoustic transformer matching system. The order of magnitude of these acoustical components is 10^{-8}.

Discussion

From this study some facts may be considered as proven:

1. The short process of the incus does not have to be considered as having a fixed point which forms the posterior end of the ossicular axis. The structure of the body of the incus allows three-dimensional movement of the incus around the malleal 'ball'. The only true axis is the malleal axis lying on a line passing through the anterior process and the malleal 'ball'.
2. The dynamics of the incudo-malleal articulation provide a three-dimensional buffered effect, maintaining the lenticular process and the stapes in a balanced vibrating position in relation to the oval window.
3. The physiological role of the middle ear is to protect the inner ear by the maintenance of a permanent equal pressure ratio between the ossicular chain and the inner ear fluids, allowing only for changes in the sound loudness pressure.
4. Individual or simultaneous voluntary or reflex activity of the middle-ear muscles, connected with the particular structure of the incudo-malleal joint, is responsible for this equilibrium.

Many physical, physiological or even pathological phenomena are explained by this hypothesis.

The movements of the drum, as recorded by the photographic studies made by Kirikae (1959), by the holographic studies done by Tonndorf and Khanna (1970) or by the stroboscopic studies of Helms (1977) are reasonably understandable, if the torsion movement of the manubrial component is added.

The action of the tensor tympani is for a balanced displacement of the manubrium, not only inwards, but also forwards. The anterior part of the pars tensa becomes relatively relaxed as compared with the increased tension of the posterior part of the drum (Fig. 19). In animals the relationship between the contracting force of the tensor tympani muscle and the stimulating sound frequency, which has a maximal force of 0·027 N or 2·7 gr: at a sound frequency of 2·700 cps. and 110 phones (as

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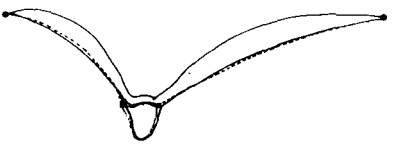


FIG. 19
Action of the force, f1, and the tympanic membrane.

proved by Kirikae in experiments on cats), is exactly the same as the flattering zone in holographic experiments on human specimens (Fig. 20). Of course this experiment must still be confirmed on wakeful normal humans, but this has not yet been done and it will be very difficult to undertake. The morphological structure of the fibrous attachment of the drum to the manubrium is strongly suggestive of the veracity of this hypothesis. Moreover, the curved membrane lever action theory, introduced by Helmholtz and more recently studied and strongly advocated by Tonndorf and Khanna (1970), is once more confirmed by this theory, because a third dimension is added.

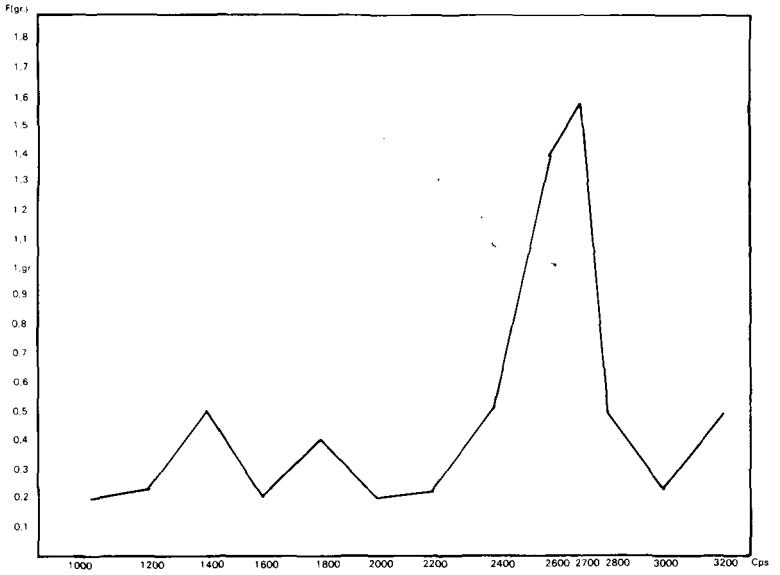


FIG. 20
Contraction in gr. of the tensor tympani, related to the frequency at a sound loudness of 100 phons (After Kirikae).

This theory is also strongly supported by clinical and experimental findings on tympanometry: for example, the fact (which has been observed by K. Van Camp and P. Van de Heyning, 1980) that removal of the incus alone, with an intact malleus and drum in place (as after translabyrinthine neurectomies) does not alter the normal tympanometric pattern, the

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system becoming more mobile. Furthermore, the normal stapes reflex as well as the 'on-off' effect becomes explicable, as also does a study of the selective contractions of the tensor tympani.

Some clinical facts can already be fully explained by our theory as, for instance, the arthritic changes in the joint, which cause a permanent hyper-pressure on the stapes and which would be responsible for unbalanced activity of the efferent fibres of the inner ear, thus resulting in tinnitus and dizziness.

Conclusion

The aim of this study was to draw attention to the role played by the mechanical component of the tympano-ossicular system, in addition to its transmitter and transformer acoustical matching system.

We hope that this work will evoke new ideas for further research on the dynamics of the ossicular chain, more particularly of the incudo-malleal joint, and on its physiology. The middle-ear muscles certainly play a much greater role in the physiology of the middle ear than is at present appreciated.

Acknowledgement

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