BONE CONDUCTION-
THE INFLUENCE OF THE MIDDLE EAR

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INTRODUCTION

The mechanism of hearing by bone conduction is a very intricate process. Its study belongs essentially to the physical field. The importance of such a study, however, lies mainly in the medical domain, because bone conduction hearing is of great diagnostic significance in otology.

In recent years the problem of bone conduction hearing has gained in clinical importance as a result of the development of the new operative possibilities in the otological field. The localization of a functional impairment of the hearing organ is generally concluded by comparing the auditory threshold for air conduction with that for bone conduction, the bone conduction threshold being regarded as a criterion for the perceptive function of the ear.

It appears, however, that the bone conduction threshold can not only be influenced by disturbances in the perceptive part of the ear, but also by disturbances of the middle ear and by changes of the external ear, the lower jaw and probably also by changes of other parts of the head.

In the present study the effect on bone conduction of various experimental and pathological changes of the middle ear apparatus, the external ear and the lower jaw are investigated. The clinical applications of these phenomena are studied and discussed. A new approach to the mechanism of bone conduction is described, based on the results found and the conclusions drawn from them.

CHAPTER I

EFFECT OF OCCLUSION OF THE EXTERNAL MEATUS

If the external auditory canal is unilaterally or bilaterally occluded while a sound stimulus is being given by bone conduction, the tone perceived becomes louder. This phenomenon is known under various names in the literature. As none of these names is particularly preferable, as will be shown, we shall speak of the *occlusion effect.*

On unilateral occlusion, this effect gives rise to localization of the sound perception in the closed-off ear. This phenomenon is called *lateralization.*

The phenomenon of 'increased' bone conduction and lateralization in the occluded ear has long been a subject of interest, as shown by the vast number of publications on it. At the present time it still draws the same attention as in former times, because the explanation of the phenomenon poses problems regarding the mechanism of hearing by bone conduction, which so far have remained without a satisfactory solution.

I. FORMER INVESTIGATIONS

History

In 1827 *Wheatstone,* the wellknown British physicist, published an article 'Experiments on audition', which has acquired historical interest. It deals with the effect of occlusion of the external meatus, as well as with the influence of a rise of pressure in the auditory canal, and of filling of the meatus with water, on the bone conduction perception. It describes how the sound of a tuning fork, placed on the skull, and that of the test subject's own voice, is heard more loudly and is localized in the occluded ear if the external meatus is closed off with the finger-tip without exerting pressure.

Tortual discovered the occlusion effect likewise in 1827, when he noticed that a watch kept against the teeth, is best heard in the ear that is closed off.

A few years later, in 1834, *Weber* also observed this remarkable phenomenon. He described it together with his well-known tuning-fork test for lateralization. In this way his discovery of the occlusion effect became best known.

Various names for the effect

Test of Bing. French authors usually speak of the 'test of Bing'. This term goes back to Bing, who, in 1891, was the first to use occlusion of the auditory canal as a method of clinical examination. He was induced to this by his finding that the occlusion effect remains absent in patients with conduction deafness, while it is normally present in patients with perception deafness.

Test of Weber. The name 'test of Weber' is often used, especially in Germany. This is very confusing, for the term: 'test of Weber' is usually employed for the lateralization test in which a tuning-fork is placed medially on the patient's skull.

It is conceivable that many misunderstandings have arisen as a result of these identical indications for two different experiments. Claus (1909) therefore suggested —in vain, however—to make a better distinction between the two by speaking of a 'physiological' and a 'pathological' test of Weber.

Test of the 'absolute bone conduction'. This term, originating from England, is derived from a certain explanation of the occlusion effect. This theory supposes that the gain of threshold is caused by the elimination—by the occlusion—of the masking influence of the ambient noise. The bone conduction threshold with occluded meatus would therefore be the true, the 'absolute' one. This theory proves to be untenable, however.

Neither on historical nor on theoretical grounds does one of these current names deserve preference; we therefore chose the neutral term: *occlusion effect.*

Measurement of the effect

The first determinations of the magnitude of the occlusion effect carried out with tuning-forks were made by Fowler sr., (1925) and by Pohlman and Kranz (1925). These were later followed by various audiometric determinations, the most important being those of Pohlman and Kranz (1926), von Békésy (1932), Kelley and Reger (1937), Sullivan, Gotlieb and Hodges (1947), and Everberg (1953). Other publications were of Aubry, Watson and Gales, Onchi and Siegenthaler et al.

Comparison of the results shows a rather good agreement. All authors found a lowering of the threshold ranging from 10 to 25 db for the lower frequencies, up to 1000 Hz. The results differ for frequencies above 2000 Hz. Usually no effect is indicated; some investigators found slight losses.

Explanation of the effect

Since a full century, investigators have occupied themselves with the explanation of the occlusion effect. One of the reasons is no doubt the general understanding that it would be possible to draw important conclusions from this phenomenon with respect to the mechanism of bone conduction hearing. Conversely, any theory of bone conduction implies an explanation of the occlusion effect. Consequently the hypothetical element has become predominant in most of the theories. The lack of sufficient proof both pro and contra each of the many theories has led to the result that, on the one hand, none of these explanations could be discarded as being superseded by the facts, while, on the other hand, none of them has been accepted to some general extent.

Remarkably enough, neither Wheatstone, Tortual nor Weber, the three discoverers of the occlusion effect, tried to give an explanation of the phenomenon. *Rinne* (1855) was the first to evolve a theory. He thought it was a question of a resonance effect in the occluded auditory canal. *Toynbee* (1860) spoke of the reflection of sound which cannot escape due to the occlusion. *Lucae* (1862, 1864) believed, in view of experiments by Politzer, that occlusion causes a rise of pressure in the auditory canal and the labyrinth. The latter would result in a better bone conduction, while the higher tension of the eardrum would also play a role.

Mach (1863) was the last investigator of this era who gave an explanation of the occlusion effect. His theory, the 'Schallabflusztheorie' (see Chapter VII), has remained, remarkably enough, of significance up to our times, although it makes a primitive impression in the light of present physical knowledge. According to Mach, occlusion impedes the 'outward flow of sound' from the cochlea to the external world. Consequently more sound energy will remain in the inner ear, which causes a loudness increase.

E. Bárány (1938) gave a quite different explanation. According to this author, the occlusion effect would arise because, due to its inertia, the occluding plug is in a relative vibratory motion with respect to the skull. This would cause a sound pressure in the auditory canal, which would lead to an increased auditory acuity for bone conduction.

Masking theory

Round about 1930 an explanation of the occlusion effect was developed which differed entirely from the former ones and which will be indicated as the *masking theory*. In this theory the threshold gain that occurs is regarded as a result of the elimination of the masking influence of the ambient noise by the occlusion. This hypothesis, advanced by Pohlman (1930), was worked out by Hallpike (1930), Dean (1930) and Bouman (1934) when it became clear to them that the occlusion effect was considerably less in a soundproof anechoic room. That it did not disappear entirely in the room might, according to these authors, be attributed to the insufficient acoustic properties of the silent room.

These investigations led to a revival of the old idea that, clinically, it would be a better method to determine the bone conduction threshold with bilateral occlusion of the auditory canals. This was expected to yield a much purer criterion for the cochlear function; hence that it was called: *absolute bone conduction.*

Others, however, like Kudson and Jones (1931), were led by their findings to oppose the masking theory, with the result that this developed into a wellknown cause of controversy.

Bone conduction by way of air conduction

According to *von Békésy* (1932), in bone conduction a sound pressure arises in the auditory canal, which besides by vibrations of the wall of this canal, would mainly be caused by relative movements of the capitulum mandibulae with respect to the wall of the auditory canal (see Chapter V). On occlusion of the meatus this sound pressure would lead to an increase of bone conduction sensitivity by air conduction way.

Later findings of von Békésy's (1941) lent support to this explanation, as no loudness increase proved to occur if the occluding plug was not placed in the opening of the auditory canal but further inwards beyond the capitulum mandibulae.

Various authors, for example Fournier (1953) and Onchi (1954) endorsed von Békésy's explanation. His theory is also found back in the present bone conduction theory, as the mechanism discussed would be one of the ways via which the bone conduction perception is brought about (see Chapter VII). In this connection the following terms are used: 'bone conduction by air' (Wever and Lawrence), 'sekundäre Luftschall' (Langenbeck), or the old name 'osteotympanic bone conduction' (Bezold).

PERSONAL EXPERIMENTS

METHODS AND APPARATUS

All investigations were carried out in a soundproof anechoic room.

The results described represent the average values of the outcomes obtained in test subjects with normal hearing.

All threshold determinations were carried out with a Peekel audiometer type D4 with an 1 db attenuator.

The intensity measurements were carried out with a Bruel and Kjaer audiofrequency spectrometer 2109. The sound probe used was made of polyaethylene. Its length was 22 cm, its diameter 0.9 mm. The results obtained were, if need be, corrected on the basis of the frequency characteristic of this probe.

§ 1. The threshold shift in the normal ear for bone conduction following occlusion of the opening of the external meatus

In 10 persons with normal hearing, the threshold shift for bone conduction was determined on occlusion of the external meatus by means of a rubber plug with a perforation of 1 mm; this perforation is necessary to prevent a rise of pressure in

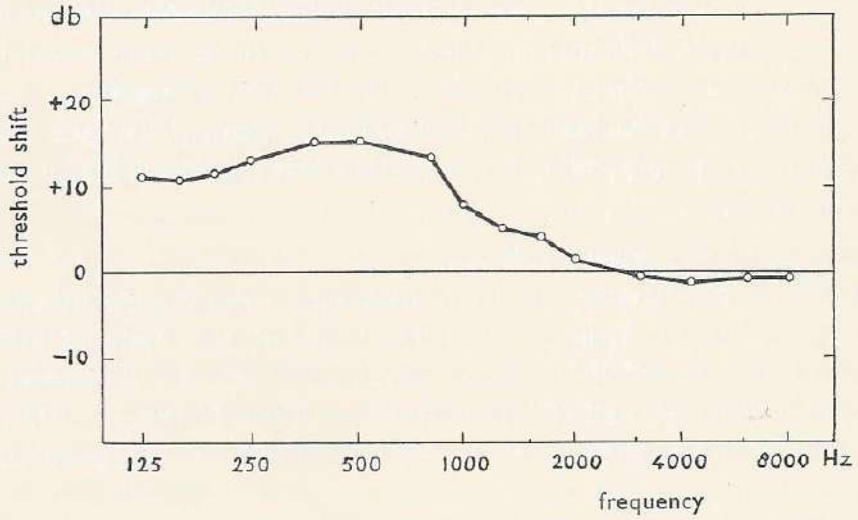

Fig. 1

Occlusion effect. Threshold shift for bone conduction following occlusion of the opening of the external auditory canal.

the external auditory canal during the placing of the plug. The bone conduction receiver was placed on the homologous mastoid.

The results represented in Fig. 1 show a threshold gain of 10-15 db for frequencies lower than 800 Hz; this threshold gain decreases gradually for higher frequencies, while above 2000 Hz it is to be neglected.

It made little difference which method was used to occlude the meatus. Fat cotton wool, a rubber plug or occlusion with the finger-tip gave the same result. The best method, however, is to close off by a plug with a tiny perforation, for reasons mentioned above.

The same results were also obtained when the bone vibrator was placed not on the mastoid but elsewhere on the skull.

The threshold shifts found were in agreement with those of other investigators both as regards the gradient of the threshold curve and the value of the shifts. We were unable to confirm two findings of other investigators.

Aubry, Watson and Gales and Everberg observed a slight threshold loss for 4000 and 8000 Hz. We failed to demonstrate such an effect in our experiments. Here it should however be taken into consideration that, on determination of the bone conduction threshold with open ear, there may be—for the high frequencies—a possibility of cross hearing by air conduction, due to the fact that the bone conductor radiates sound energy into the air. If this is the case, an apparent threshold loss may be found on occlusion.

Onchi found peaks in his curve of the threshold gain on occlusion at 200 and 800 Hz. He attributed these to a resonance effect of the eardrum and of the ossicular chain. In spite of our using continuous audiometry, which may be considered the method of choice for the demonstration of such peaks, we did not succeed in confirming these findings.

§ 2. The occlusion effect as a function of the ambient noise intensity level

As remarked before, in the 'masking theory' the occlusion effect is attributed to the elimination of the masking influence of the ambient noise. To study this explanation, the relationship between the magnitude of the occlusion effect and the ambient noise intensity level, was investigated.

This investigation took place in the soundproof anechoic room of the Dr. Neher Laboratory of the Netherlands P.T.T. In this room, the residual noise intensity level proved to be less than the natural disturbance level (22-27 db) of a General Radio sound level meter. This means that is was below the level of 30-35 db, which is to be regarded as the level at which masking begins.

Also in this soundproof anechoic room a lowering of the threshold by 10-15 db was observed on occlusion. Everberg (1953) also found that the occlusion effect persists in a soundproof anechoic room of high quality.

If the intensity of the background noise was artificially amplified by applying a white noise, the occlusion effect, too, increased proportionally, as shown in the curve of Fig. 2 for a frequency of 500 Hz. No further increase of the effect occurred when the level of the ambient noise rose above 65 db. In this case a

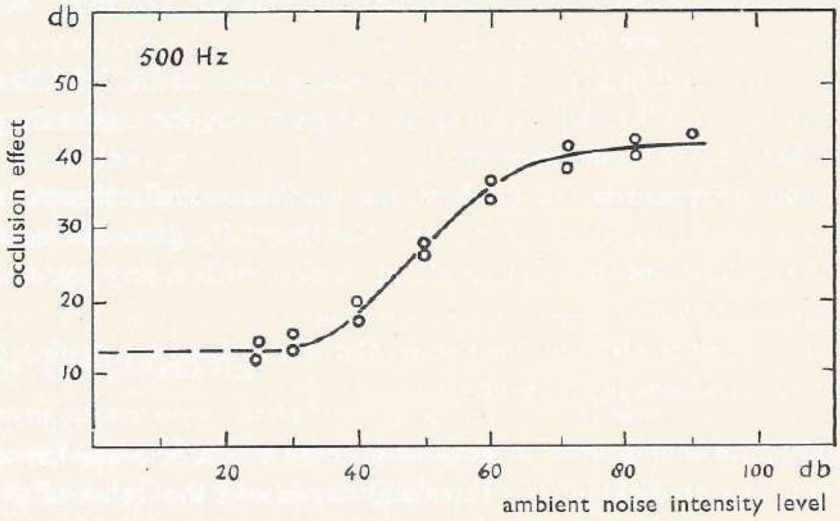

Fig. 2
Occlusion effect as a function of the ambient noise intensity level.

masking effect began to develop also during the occlusion, as the occlusion did not weaken the masking noise by more than 30 db.
These results demonstrate that the normal occlusion effect can not be explained as a result of elimination of a masking influence of the ambient noise. This mechanism will only cause a certain strengthening of the occlusion effect, dependent on the intensity level of the ambient noise.

§ 3. The occlusion effect as a function of the point of occlusion

By lengthening the external auditory canal with a tube of the same diameter and by occluding this at varying distances from the eardrum, the effect on bone conduction threshold proved to change in a special way. It was found that the value of the effect depends on the distance of the point of occlusion from the tympanic membrane, and that for occlusion at certain distances the effect may be absent or that it may even become negative.

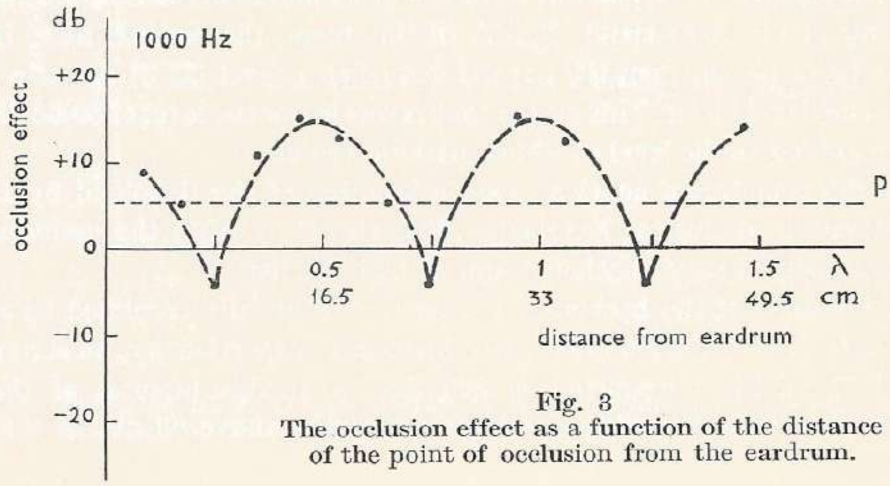

Fig. 3
The occlusion effect as a function of the distance of the point of occlusion from the eardrum.

When, like indicated in Fig. 3 for a frequency of 1000 Hz, the auditory canal was not closed off at its opening but successively at increasing distances from the eardrum, the occlusion effect decreased gradually. Finally it disappeared and changed of sign. This *negative* occlusion effect—which means a loudness decrease of the bone conduction tone on occlusion—was strongest at occlusion at a distance of one-fourth of a wavelength ($\frac{1}{4}$ λ). It amounted to 3-5 db.

Occlusion at greater distances caused again a positive occlusion effect, which became gradually greater to reach a maximum at occlusion at a distance of $\frac{1}{2}$ λ from the eardrum. For 1000 Hz this effect amounted, on an average, to 13 db.

This variable occlusion effect is graphically represented in Fig. 3, after conversion of the magnitude of the effect to the normal threshold with an open meatus. The changes perceived by the test subjects concerned those with regard to threshold on extension of the auditory canal with the tube used (length 50 cm, diameter 0.9 cm). This threshold is indicated in the figure as the dotted line p; the sensitivity of the ear was, for the frequency used, 5 db higher after the tube had been placed against the ear.

The same results were obtained for frequencies of 500 and 800 Hz. Corresponding results were also found when a tube with a diameter of 2 cm was used.

The points of occlusion where the greatest negative occlusion effect was found, were indicated very sharply up to an accuracy of 0.5 cm. They coincided exactly with distances of $\frac{1}{4}$ λ, $\frac{3}{4}$ λ, etc. from the eardrum.

In contrast with this, the maximum occlusion effect was not sharply localized, as shown by the blunt peaks besides the sharp dips of the curve in Fig. 3. The maxima were found at distances of 0.45 λ, 0.95 λ from the eardrum.

The typical shape of these curves with blunt peaks and sharp dips is fully in agreement with sound pressure distribution as a function of distance in a similar 'impedance tube' as is described by Beranek in his book 'Acoustic Measurements' p. 322.

When seeking for an explanation of these findings, it is selfevident to think of a resonance phenomenon with a standing wave motion in the occluded auditory canal.

To confirm this, sound pressure measurements were carried out in the auditory canal and in the extension piece. The typical course of the curve of Fig. 3 was also found for the curves of the sound pressure determined (a) at a distance of $\frac{1}{4}$ λ from the eardrum, and (b) at the eardrum itself. Fig. 4 shows these sound pressure curves together with the corresponding threshold shift.

It appears that the curve of the sound pressure at the eardrum (b) is in phase with that of the occlusion effect (c). Quite in agreement with this, the curve of the sound pressure at $\frac{1}{4}$ λ has shifted 90° with respect to the latter.

The figure shows that maximum sound pressures were measured at $\frac{1}{4}$ λ from the eardrum for occlusion at $\frac{1}{4}$ λ, $\frac{3}{4}$ λ, $\frac{5}{4}$ λ, etc., distance from the eardrum. This maximum sound pressure at $\frac{1}{4}$ λ is attended by a minimum sound pressure at the eardrum and a maximum negative occlusion effect. The opposite is observed for occlusion at $\frac{1}{2}$ λ, 1 λ, etc.

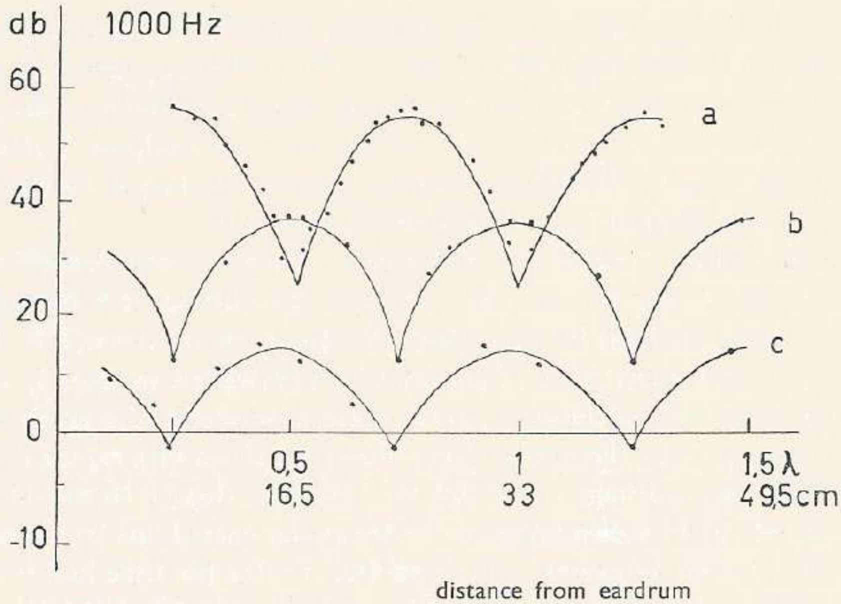

Fig. 4

Sound pressure curves: (*a*) at $\frac{1}{4}\lambda$ distance from the eardrum, (*b*) at the eardrum, with corresponding curve of occlusion effect (*c*).

Fig. 4 also shows that a difference exists in amplitude between the three curves.

As regards the curves *a* and *b*, the explanation may be given by the different conditions at the points of measurement concerned. The eardrum is a flexible membrane and the wall of the auditory canal exerts a somewhat damping influence, whereas the measurements at $\frac{1}{4}\lambda$ took place in a copper tube, which implies that here the sound pressure will rise to higher values. The difference in amplitude between curves *b* and *c* means that a quantitative difference was found between the change of the sound pressure at the eardrum and the magnitude of the occlusion effect. This will be dealt with in more detail in § 4.

The results of the experiments described lead to the conclusion: that the value of the occlusion effect depends on the distance of the point of occlusion from the eardrum.

The effect has to be attributed to an effect of standing wave movements which means the coupling of a certain other impedance to the ear, as will be discussed in § 5.

§ 4. The increase of sound pressure at the eardrum and threshold shift after occlusion

When discussing the measurements represented in Fig. 4, the remark has been made that a quantitative difference was found between the increase of the sound pressure at the eardrum and the threshold shift caused by occlusion. This finding was checked at other frequencies.

The value of this difference as a function of frequency in case of occlusion of the meatal opening is shown in Fig. 5. There seems to be no particular constant corre-

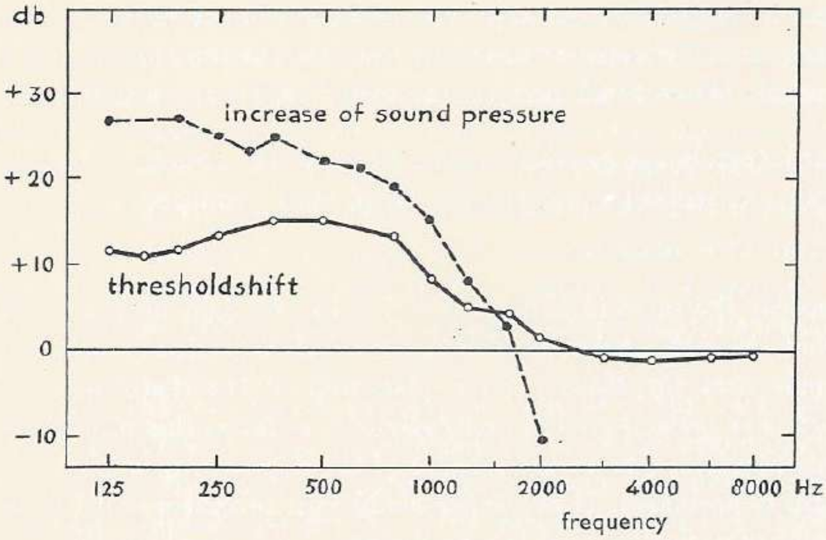

Fig. 5

Increase of sound pressure at the eardrum and the accompanying threshold shift for various frequencies after occlusion of the meatal opening.

lation between the increase of sound pressure measured and the accompanying threshold shift.

The declining course of the curve showing the increase in sound pressure is understandable, as for rising frequencies the distance from the place of occlusion to the eardrum, i.e., the distance tragus-eardrum, (2.5 cm.) approaches the value of $\frac{1}{4}\ \lambda$, for which the sound pressure at the eardrum is minimal ($\frac{1}{4}\ \lambda = 2.5$ cm at 3300 Hz).

For frequencies exceeding 1500 Hz the sound pressure proved to decrease markedly, and for frequencies higher than 2500 Hz it was too low to be measured with the method used. The sound pressure at 2000 Hz proved to be brought about by sound energy radiated into the air by the bone conduction receiver, reaching the meatus by air conduction. Hence that at this frequency a decrease was found on occlusion.

§ 5. Conclusions; explanation of the effect

The results of our experiments on the effect of occlusion can be summarized in the following conclusions:

1. Occlusion of the meatal opening caused a threshold gain for bone conduction of 10-15 db for frequencies up to 1000 Hz; for higher frequencies this effect decreased while above 2000 Hz no threshold shift occurred.

2. This occlusion effect persisted in a soundproof anechoic room with a residual noise below masking threshold. Increase of the ambient noise intensity level to values higher than 35 db caused a proportionate increase of the occlusion effect.

3. As regards magnitude and sign, the occlusion effect proved to be dependant on the distance of the point of occlusion from the eardrum: occlusion at $\frac{1}{2}$ λ, λ etc. caused a maximal threshold gain, occlusion at $\frac{1}{4}$ λ, $\frac{3}{4}$ λ etc. a slight threshold loss.

4. No fixed correlation proved to exist between the change of sound pressure at the eardrum on occlusion and the threshold shift produced.

If we consider the most important theories in the light of the results obtained, they prove to be not consistent with these results in various respects.

This holds first for Mach's old explanation of the disturbed 'Schallabfluss'. This theory is at present greatly contradicted—as far as this primitive explanation needs contradiction—due to the finding of the dependence of the occlusion effect on the point of occlusion. That the threshold shift increases or decreases by changing the point of occlusion, that it may disappear and may even become negative, is entirely contrary to the explanation of the disturbed 'Schallabfluss'.

The masking theory is also contradicted in these investigations. It appeared that elimination of a masking influence of ambient noise cannot be the mechanism proper of the occlusion phenomenon, but that it only strengthens the effect, dependent on the intensity level of the ambient noise.

Neither is the explanation that the occlusion effect would result from an increase of the air conduction factor of the bone conduction caused by the occlusion, in agreement with the results obtained. It appeared that increase of the sound pressure at the eardrum does not correspond with the threshold gain in a way as would be expected if this were due to the incraese of sound pressure, as suggested in this theory. It does not seem to be, as was supposed by von Békésy, that during occlusion, bone conduction perception is brought about by the sound pressure, in the way of an air conduction stimulus. Nor does the finding that on occlusion at $\frac{1}{4}$ λ a slight threshold loss occurred, agree with this idea.

In view of the experimental results, another explanation of the occlusion effect seems therefore indicated.

It is evident that on occlusion an air column of particular properties is suddenly coupled to the vibratory system of the middle ear and the cochlea, instead of the ambient air. Also without fully knowing this system, it is understandable that thus the vibratory motion of this system is changed and with this the sensitivity of the ear. Instead of the low impedance of the ambient air, a closed off air column with a quite different impedance has become part of the system. The value of the impedance of this air column will depend on its length in relation to the frequency used, namely whether there is resonance, antiresonance or a condition in between.

First the situation is considered for occlusion at a distance of $\frac{1}{4}$ λ, $\frac{3}{4}$ λ, etc. from the eardrum. In this case the air column is in resonance; there is an antinode at the eardrum (minimum sound pressure, see Fig. 4) and this means coupling of an *minimal* ($\rightarrow$ 0) impedance, i.e., even lower than the impedance of the ambient air.

If this condition is regarded from a viewpoint of energy relationships, it is clear that, as a result of this state of resonance, the uptake of energy by the tube will be maximal. This means that the cochlea will receive less energy as compared with the situatiation with open meatus, which results in a slight threshold loss.

The opposite is the case when the air column is adjusted to the state of antiresonance (occlusion at $\frac{1}{2}\lambda$, λ, etc.). Now an antinode exists at the eardrum (maximum sound pressure, see Fig. 4), and a *maximal* impedance is coupled to the ear. Now less energy will be transmitted compared with the situation with open meatus, which means that the threshold is lowered. The situation that presents itself on occlusion at intermediate distances, like, for example at the meatal opening, speaks for itself.

In § 5 a difference has been found between the increase of the sound pressure at the eardrum and the threshold gain on occlusion of the meatal opening. Physically, this is understandable, because there exists never a simple relationship between the amplitudes of two coupled systems (i.e., the inner ear and the external ear). Moreover, in the case concerned a third system (the middle ear apparatus) is situated between the other two.

§ 6. Clinical aspects of the occlusion effect

a. The occlusion effect as a diagnostic aid

The occlusion effect may serve as a simple means of differentiating between a conduction deafness and a perception deafness, as indicated by Bing in 1891 and later drawn into the attention again by Aubry (1945). It appears that in the case of a conduction deafness no increase of loudness is observed on occlusion of the auditory canal, whereas the normal occlusion effect is experienced in the case of a perception deafness.

The absence of the occlusion effect in conduction disturbances is readily explainable, as it is evident that occlusion of the meatus will only be able to influence the auditory threshold if the function of the transmission apparatus is sufficient. If the occlusion effect is regarded as a result of the coupling of another impedance to the middle ear, it is understandable that the magnitude of the effect also depends on the conductive function.

A personal investigation into the occlusion test was carried out in some hundreds of persons with conduction deafness, perception deafness, and also with normal hearing. The following results were obtained:

1. In almost all cases the test proved to be a reliable differential diagnostic means: *in conduction deafness the effect of occlusion is absent, in perception deafness it is normally present.* The examination can fail in some less intelligent subjects because the increase of loudness is probably too slight to be satisfactorily observed by them.

2. In the case of a conductive impairment of less than 20 db, an occlusion effect was sometimes still observed. This is no cause for wonder, as the magnitude of the effect, like remarked before, is also dependent on the degree of the conductive loss.

3. The optimal frequency range for the occlusion test lies between 500 and 1000 Hz, as for these frequencies the loudness increase is strongest, the conditions for the use of a tuning-fork also being favourable.

We may conclude that the occlusion test —as also pointed out by various French authors—has the same value as the better known tuning-fork test of Weber and of Rinne.

It is important here to emphasize that the occlusion effect is absent in *all* forms of conduction deafness. The test is therefore not to be considered specific for otosclerosis, as very often suggested, especially in France.

b. The 'faux-Bing' phenomenon of Fournier

In 1953 Fournier described the phenomenon that if, in a patient with unilateral conduction deafness with lateralization to the diseased ear, the healthy ear is occluded the increase of loudness caused by this occlusion is perceived in the diseased ear. Fournier called this phenomenon 'faux-Bing'. According to Fournier (1954), it cannot be explained with the help of the present bone conduction theory; the 'faux-Bing' would even be contradictory to this theory.

The 'faux-Bing' phenomenon was studied by us in more detail in 50 patients with an unilateral conductive impairment. The investigations were carried out with a bone conduction stimulus of 500 Hz applied to the forehead. All patients lateralized this bone conduction tone in the diseased ear.

We investigated:

1. whether on occlusion of the normal ear an increase of loudness was observed and *where* this loudness increase was perceived.

2. whether a *change in the lateralization impression* occurred at the same time. If the test subject indicated a change in sound localization his statement was verified. This was done by comparing his localization impression with open ear with that during occlusion.

TABEL I

conductive loss in db	number	lateralization impression			
		stronger	weaker	medially	other ear
< 20	17	1	0	2	15
20 — < 30	22	3	5	9	3
30 — < 40	8	1	5	3	0
40 — < 50	3	2	1	0	0
Total	50	7	11	14	18

The results obtained are given in Table I. All patients indicated an increase of loudness on occlusion of the normal ear. This loudness increase was perceived on the side where the tone was lateralized but in most cases a change in this lateralization impression was observed at the same time.

The degree of this change of lateralization impression seemed roughly correlated with the extent of conductive loss:

1. In most of the patients with a conduction loss of less than 20 db, a *reversal* of the lateralization to the normal ear was found on occlusion of this ear.

2. With a loss of 20-40 db, a *decrease* of the degree of lateralization in the diseased ear or a medialward shift of the sound localization was usually indicated.

3. Seven patients observed an *increase* of the lateralization impression in the diseased ear.

It was difficult to find out in which way the impression of the lateralization exactly changes, if this remains at the same side. Thus it is possible that the seven patients who stated a magnification of the lateralization impression, did so incorrectly. It is conceivable that they wrongly interpreted the increase of loudness observed in the affected ear as a stronger lateralization.

The shift of the sound localization to the middle of the head (present in 14 patients) and the reversal of the sound localization to the other ear (present in 18 patients) was generally clearly to be observed. In most cases these changes were mentioned spontaneously. Moreover they could be checked by the method described.

The explanation of the 'faux-Bing' phenomenon need not raise much problems in our opinion. No help of a special theory like that of Langenbeck (1954) seems to be necessary. It is a phenomenon that is to be expected, as has been confirmed by the results described.

When a bone conduction stimulus is applied medially on the skull both ears are stimulated, in which one single sound sensation arises. This sound sensation is attributed a certain spatial localization, depending on differences between the impulses from the left and the right and their central elaboration. In case of a unilateral conductive deafness—for reasons not to be discussed now—lateralization towards the diseased ear occurs. The strenght of the sensation, or in other words the loudness of the tone perceived in this ear, will be determined by the threshold of the ear that hears best by bone conduction.

If the loudness of the tone is increased, for example because a stronger impulse is given, or because the bone conduction threshold of the best ear is lowered by occlusion, this loudness increase will of course be observed in the ear where the tone was localized. It is possible however, as in the case of occlusion, that with this loudness increase the localization impression also changes because the relationship between the stimuli arriving from the left and the right changes as well. Thus it is understandable that in patients with a slight conductive loss a reversal of the lateralization was found. In a similar way it can be explained why a median localization often occurred in cases with a moderate loss, whereas in patients with great losses the lateralization in the diseased ear appeared to persist. In the latter cases it is theoretically to be expected that the lateralization will become less marked.

'absolute bone conduction'. English authors formerly (Comm. of Res. Roy. Soc. 1917, 1933, Clarke 1929, Hastings 1929, Hallpike 1933, McNally c.s. 1937) recommended to close off both auditory canals in bone conduction audiometry, in order to eliminate the masking influence of the ambient noise, so that the real, 'absolute' bone conduction threshold would be measured. This advice was related with the investigations mentioned before, which have led to the masking theory as an explanation for the occlusion effect. It seems that this method has not been used very often, although also in recent times a paper on its use has been published (Clemente, 1951).

It is however evident, also on the basis of our personal experiments, that bone conduction audiometry with an occluded auditory canal should be considered incorrect. It has been shown that—at any rate in relatively silent surroundings—the threshold gain by occlusion is not based on elimination of a masking effect. We found that it arises because instead of the ambient air a closed-off air column with a higher impedance is coupled to the ear. The bone conduction threshold found during occlusion is therefore a less satisfactory criterion for the cochlear function, instead of being a better one. During occlusion the conduction apparatus plays an even greater role in bringing about the bone conduction perception.

It is therefore better to discard as well the term 'absolute bone conduction', used especially in France to indicate bone conduction with a closed meatus, in contrast to that with an open auditory canal (conduction osseuse absolue, C.O.A.—conduction osseuse relative, C.O.R.), as the 'relative' bone conduction appears to be a better criterion than the 'absolute', at any rate in silent surroundings. If we wish to preserve the term 'absolute bone conduction', it should be reserved for that form of 'bone conduction' which—as was meant by the term—gives a purer criterion for the cochlear function.

Errors in bone conduction audiometry caused by an occlusion effect of the telephone receiver. In bone conduction audiometry the ear not under test is generally excluded by a masking noise administered by means of a headphone. As the use of a headphone implies an occlusion of the ear, we measured the magnitude of the occlusion effect caused by the different types of air conduction receiver.

The flat type telephone receiver of, for example, the Peekel, the Peeters and the Atlas audiometer, proved to cause a threshold gain of 5-10 db for the low frequencies. No such occlusion effect occurred when the loudspeaker type of the Danish Pedersen audiometer was used. This telephone receiver possesses a free volume of about 375 ml and it is further filled up with a stiff pad of cotton wool, so that an almost infinite space is adapted to the ear. No thresholdshift will occur when this receiver is used as no changes arise in the impedance coupled to the middle ear. Thus the bone conduction threshold remains unchanged.

The flat type telephone receiver may therefore cause serious errors in bone conduction audiometry, if care is not taken that only the ear to be masked is covered by the headphone, especially so because, as has already been discussed, the occlusion effect varies in degree in different forms of deafness. The error that may be made will therefore not be constant. The loudspeaker type of receiver is therefore preferable for bone conduction examination, just as for air conduction, as demonstrated by Groen (1953). If a flat telephone receiver is used, a rule always to be observed in bone conduction audiometry is *that the ear under examination be always free.*

CHAPTER II

EFFECT OF AIR PRESSURE CHANGE

Producing a positive or a negative change of air pressure in the external auditory canal or in the tympanic cavity gives rise to a change in sensitivity for air as well as for bone conduction hearing. Like the occlusion effect, the effect of a change of pressure on hearing acuity has been a subject of interest for more than a century. Theoretically, this effect is of importance in connection with the mechanism of the air and bone conduction perception; clinically, it has led to the elaboration of certain methods of investigation, e.g., the test of Gellé and the pneumophone of van Dishoeck.

This chapter deals in the first place with the influence of changes of air pressure on bone conduction, as part of our bone conduction studies. However, this cannot be done properly without also paying attention to the effect on air conduction.

I. FORMER INVESTIGATIONS

History

Wheatstone is in general called the discoverer of the effect of pressure changes on the auditory acuity. This is correct as regards bone conduction, as, in his above-mentioned publication of 1827, Wheatstone described how a bone conduction tone becomes weaker if the air pressure in the auditory canal is raised by pressing the finger into the meatus.

Wollaston, however, proves to have preceded him in describing this effect in the case of air conduction. He noticed that the auditory acuity decreases if a rise of pressure is produced in the tympanic cavity by means of the test of Valsava. Wollaston's description is the more remarkable because he also mentioned a difference in influence on low tones as compared with high tones, whereas he seeks the explanation in an increased tension of the eardrum.

Test of Gellé

In 1881 Gellé reported a clinical application of the effect of change of pressure, by means of which a stapedial ankylosis were to be diagnosed. He found that, while normally exertion of pressure on the tympanic membrane causes a decrease of loudness for air as well as for bone conduction (*positive Gellé*), on fixation of the stapes there is no effect on bone conduction, whereas that on air conduction is preserved (*negative Gellé*).

Although this fact had also been found by Lucae as far back as 1863, this method of examination has rightly become known under the name of test of Gellé.

In the beginning this test did not come into use as a diagnostic means, due to criticisms by for example Politzer, and by Bezold as regards its explanation. It was not accepted as such until after 1890, when its clinical usefulness was successively confirmed by Rohrer, Argentowsky, Bloch and Brühl.

In 1921 Griessman described an instrument designed to carry out the examination quantitatively, the 'otosclerometer'. However, exact study and systematic clinical application did not become of significance until the introduction of the audiometer and of the pneumophone of van Dishoeck in 1937. Quantitative clinical studies have since been carried out by Aubry and Giraud (1943), Zangemeister and Kietz (1953) and especially by Thullen (1954) and by Dudok de Wit and van Dishoeck (1959).

Measurements of the effect

The first investigations of the magnitude and frequency dependence of the effect of pressure changes were carried out by Mach and Kessel (1872) and later by Pohlman and Kranz (1923, 1925, 1926) and by von Békésy (1929, 1932). They found a decreased auditory acuity both for air and bone conduction, especially for the lower frequencies. Accurate measurements by means of the pneumophone and audiometer were carried out by van Dishoeck in 1940. He found a threshold loss for the lower and middle tones, decreasing in magnitude with rising frequency both in air and bone conduction, as well as for positive and negative changes of pressure. A slight threshold gain was sometimes measured at 4000 Hz. The loss of hearing was greater for air conduction than for bone conduction, while the effect of positive pressure change was somewhat greater than that of a negative one. These results were later confirmed by others, in particular by Rasmussen (1946, 1948).

Various authors have however expressed their doubts whether the threshold shift found for bone conduction, is a real effect of the pressure change. Aubry, Fournier (1953) and Onchi (1954) regarded the threshold loss found for bone conduction as an artefact. According to these authors, the production of a change of pressure in the auditory canal is unavoidably accompanied by occlusion; what is considered as an effect of change of pressure, would therefore be nothing else but the abolition of a previous threshold gain caused by occlusion.

Change of air pressure in the tympanic cavity

If a change of air pressure is brought about in the tympanic cavity with the help of Valsava's test, the auditory acuity for air and bone conduction is diminished, as discovered by Wollaston. Bezold (1888) and Siebenman (1982) later obtained contradictory results when applying this test; Gatscher (1917), on the other hand, again found a decrease of loudness.

Newer investigations, in which a positive and sometimes also a negative change of pressure was created in the tympanic cavity, were carried out by Fowler sr., (1920), Loch (1942) and Tarab (1958) for air and bone conduction, and by E. Bárány (1938) for bone conduction alone. All authors found greater or smaller losses, which were strongest for the lower frequencies. In none of these investigations, however, was the magnitude of the changes of pressure produced, determined.

Animal experiments

The effect of pressure changes on the auditory acuity has also been studied in animal experiments. Thompson, Howe and Hughson, (1934) Wever et al. (1942, 1948) and Rahm, Strohter and Crump (1956) and took the cochlear potentials as a criterion; Kobrak (1935) used the tensor tympani reflex. Their experiments generally confirmed the audiometric results obtained in man.

Explanation

Effect on air conduction. The theory of Gellé that an increase of pressure, by producing an inward movement of the stapes (*'pressions centripètes'*), would give rise to an increase of pressure in the labyrinth and thus to a decrease of auditory acuity, has proved untenable, for various reasons. Important arguments against it are: 1. a negative change of pressure has almost the same influence as a positive; 2. no decrease of auditory acuity occurs if the labyrinthine pressure is increased via another method, for example by congestion of the jugular veins; 3. the loss of hearing remains the same for constant pressure, while it may safely be assumed that a rise of liquor pressure, if any, will disappear very soon again.

Later authors, e.g. van Dishoeck (1939), arrived at the conclusion that it is the eardrum and the ossicular chain that constitute the point of action of the pressure change. This explanation was supported by measurements carried out by von Békésy in 1932, which showed that, on rise of pressure, the impedance of the eardrum increases proportionately with the magnitude of the hearing loss. Finally, in 1948 Henrik Johansen succeeded in fully explaining the effect of pressure changes for *air conduction*, as found by van Dishoeck and by Rasmussen, as an effect on the middle ear apparatus. If the eardrum is subjected to a unilateral pressure, the stiffness of the conduction apparatus will be increased. Application of the impedance formula

$$Z = \sqrt{Rm^2 + \left(2\pi f.m - \frac{S}{2\pi f}\right)^2}$$

shows that the impedance Z increases if the stiffness S becomes greater, which means that the auditory acuity decreases. This increase of impedance is greater the smaller the frequency f. That sometimes a hearing gain was found for 4000 Hz, was attributed by Johansen to a shift of the resonance point of the ear to a higher frequency as a result of the increase of its stiffness.

The explanation of the bone conduction loss has drawn relatively little attention. The fact that the bone conduction effect corresponded qualitatively with that on air conduction, led Pohlman and Kranz (1926), von Békésy (1932) and van Dishoeck (1940) to the conclusion that this bone conduction effect is due to an influence exerted on the 'air conduction factor of bone conduction', also called the 'osteotympanic factor' of bone conduction.

Another explanation was given by E. Bárány (1938), based on his finding that for low frequencies bone conduction is brought about by movements of the ossicular chain relative to the cochlear capsule, the so-called 'inertia bone conduction'. Like in air conduction, pressure change would impede these relative oscillations, so that a threshold loss for bone conduction would occur as a result of a decrease of this 'inertia bone conduction'.

Both explanations are however not able to account sufficiently for all phenomena, at any rate in the way in which these explanations are given. It remains unexplained why the threshold loss also occurs for the middle frequencies and why a threshold gain was found for frequencies higher than 4000 Hz. It remains likewise unsolved why the effect on bone conduction is smaller than that on air conduction. These problems will be dealt with in more detail in § 6 after the description of our personal experiments.

II. PERSONAL EXPERIMENTS

METHODS AND APPARATUS

For the general methods of investigation, reference is made to Chapter I.

The pneumophone of van Dishoeck was used to produce air pressure changes in combination with a sound stimulus. The telephone contained in the pneumophone possesses a perforated membrane, so that the sound stimulus produced cannot be influenced by pressure variations. This telephone was fed by an audiometer with an 1 db attenuator.

§ 1. The threshold shift for bone conduction following change of air pressure in the external auditory canal as a function of frequency

In 8 persons with normal hearing the threshold shift for bone conduction was determined after a positive or negative change of air pressure of 50 cm water was brought about in the external auditory canal.

The method used in this investigation is of great importance, because the production of a change of pressure in the external auditory canal unavoidably leads to occlusion of the latter. This means that an occlusion effect will occur, which causes a threshold gain. As mentioned before the finding of a bone conduction loss on air pressure change, would therefore, according to various authors mean nothing but an abolition of a gain previously caused by occlusion. It is however possible to avoid the occurrence of an occlusion effect by using the experiences earlier obtained with respect to this effect. As described in Chapter I, the magnitude of the occlusion effect proved to be dependent on the distance of the point of occlusion from the eardrum.

As shown by Fig. 3 no threshold shift at all was found when the meatus was occluded at a distance of about $\frac{1}{5}$ λ from the eardrum. Our investigations of the effect of air pressure change on bone conduction sensitivity were therefore carried out during occlusion at $\frac{1}{5}$ λ (A). The change of air pressure was effected via a narrow communication (B) with the connection piece as shown in Fig. 6.
This method can not be used for frequencies higher than 2000 Hz, occlusion at $\frac{1}{5}$ λ then being impossible because this distance becomes smaller than the length of the auditory canal with connection piece (3.5 cm). As, however, no occlusion

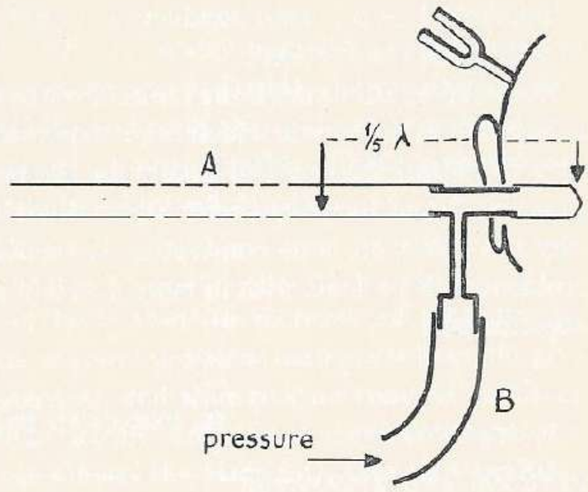

Fig. 6
Method for measuring the effect of air pressure change in the external meatus on bone conduction sensitivity, with exclusion of the occlusion effect.

effect occurs for frequencies above 2000 Hz, the occlusion can then be created at any point.

The threshold shift for bone conduction found with this method for a positive or negative change of pressure of 50 cm water is shown in Fig. 7.

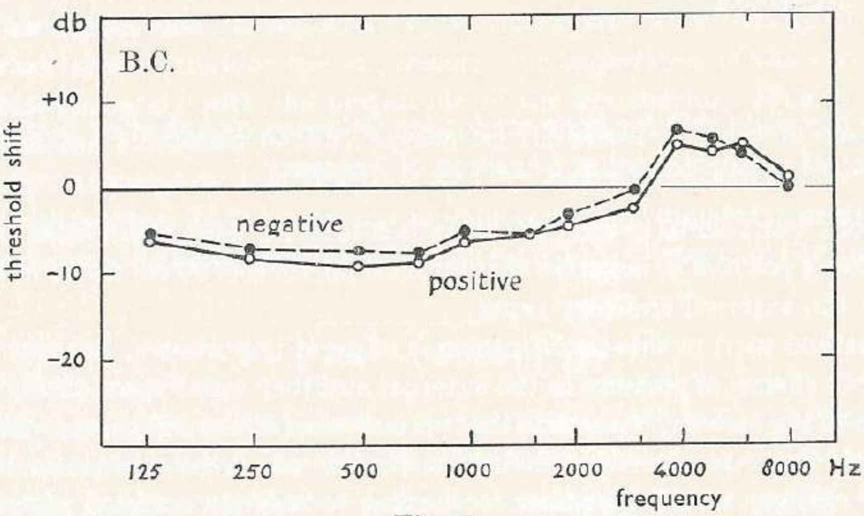

Fig. 7
Threshold shift for bone conduction following a positive or negative change of air pressure of 50 cm water in the external auditory canal.

It appeared that, both for positive and negative changes of pressure, a threshold loss of 5-10 db occurred for the lower frequencies, with a maximum of 10 db at 500-800 Hz; with rising frequency this loss declined gradually and changed into a threshold gain of 5 db at about 4000 Hz.

In Fig. 8 the effect of a positive or negative change of pressure of 50 cm water on the *air conduction* threshold is demonstrated.

The curve for air conduction is qualitatively equal to that for bone conduction. There is however a marked quantitative difference. The threshold shift for air conduction is about 1½-2 times as great as that for bone conduction.

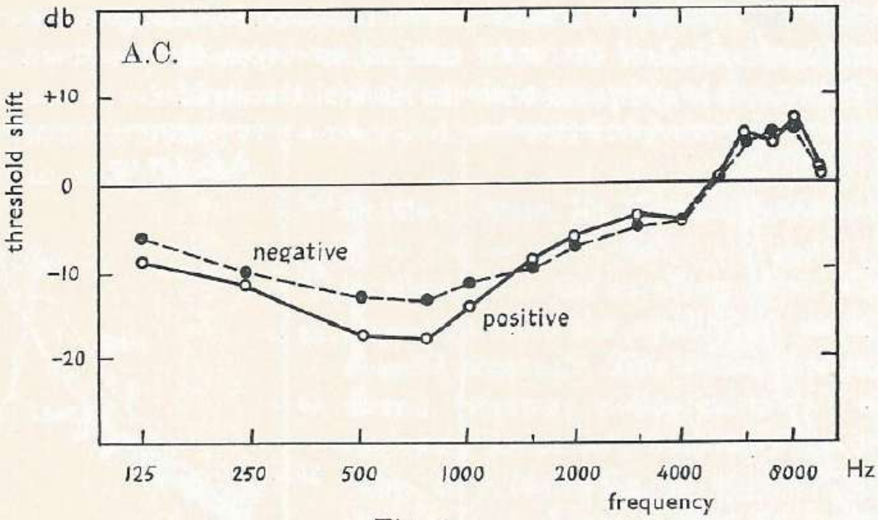

Fig. 8

Threshold shift for air conduction following a positive or negative change of air pressure of 50 cm water in the external auditory canal.

The results are essentially consistent with those obtained by van Dishoeck, Rasmussen, and other investigators. The effect for bone conduction found by us is smaller than that recorded in their investigations, which may be a result of the fact that they did not take measures to avoid the occlusion effect.

Von Békésy avoided the disturbing influence of the occlusion effect by bringing about the pressure changes by means of a pressure chamber attached to the skull; thus the auditory canal remained entirely free.

Our results were checked with a method based on this principle. The change of pressure was produced with a metal box of 1000 ml contents, lined internally with sound absorbing material. On occlusion with such a volume no threshold shift occurs for frequencies of 256 Hz and higher, as has been found by Watson and Gales (1943).

§ 2. The threshold shift for bone conduction as a function of the change of air pressure

The magnitude of the threshold shift caused by the production of a positive or negative change of pressure, depends on the magnitude of this pressure change. This dependence was studied for different frequencies, for bone conduction as well as for air conduction. The method employed was not—as might be expected—the determination of the magnitude of the threshold shift for different values of pressure change. Measurements of a markedly greater accuracy are possible, by investigating which values of pressure change are necessary and sufficient for just abolishing the perception of a tone of a given intensity. This method is exact and simple, because the changing of the pressure can be realized continuously by means of the Politzer balloon of the pneumophone. It is possible to determine a few times in a short time and in rapid succession at which pressure the tone exactly disappears or is just perceived again. The average of these values was used as a measuring point for the curve.

In § 7 this more accurate method is also proposed for the quantitative clinical determinations instead of the usual method, in which the threshold at a given change of pressure is compared with the normal threshold.

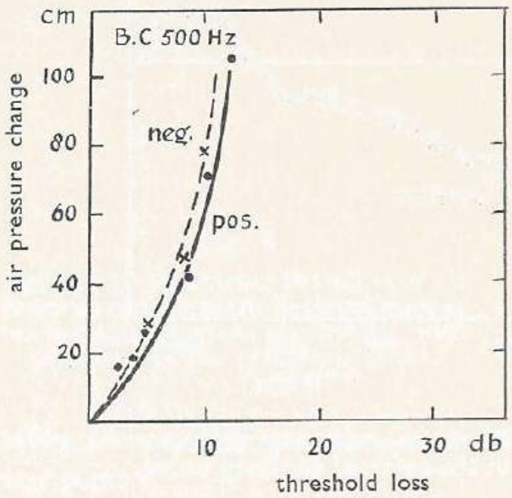

Fig. 9
Threshold shift for bone conduction as a function of change of air pressure.

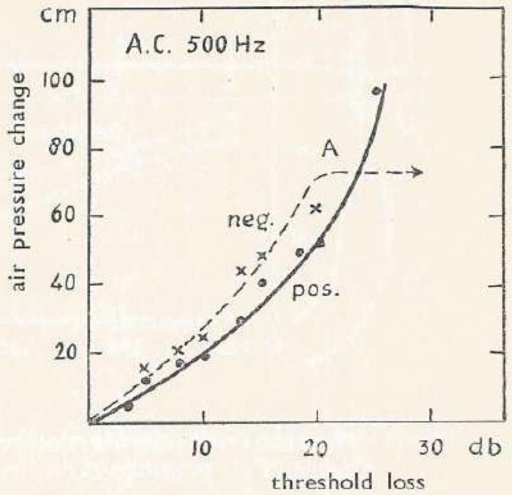

Fig. 10
Threshold shift for air conduction as a function of change of air pressure.

Figs. 9 and 10 represent the curves found for 500 Hz for bone and air conduction, both for positive and negative pressure changes. The course of the curve is asymptotic, as was to be expected. The maximum sound intensity that could be made inaudible by changing the pressure, was about 25 db for air conduction and about 15 db for bone conduction. It became also evident that the effect of a positive change of pressure is somewhat greater than that of a negative change.

If, in the experiments for air conduction, the negative pressure changes were increased to more than 60-80 cm water, various test subjects suffered a sudden threshold loss of 20-30 db (point A in Fig. 10). This phenomenon was also observed by van Dishoeck; this author thought of the possibility of a luxation of the stapedo-incudal joint.

However, by producing in such cases the change of pressure via a Siegle's-otoscope, it was found out that this phenomenon was due to inward suctioning of the skin of the auditory canal by negative pressure, which led to the occlusion of the ear canal.

§ 3. The effect of positive change of air pressure in comparison with that of a negative change

In the literature mention is always made of an equal effect of positive and negative change of pressure. This fact is used as an argument for the contention that the eardrum and the ossicular chain constitute the point of action of the effect. However, in the experiments of § 2 its was found that the effect of positive pressure change is distinctly greater than that brought about by a negative pressure change.

In a system like that formed by eardrum and auditory ossicles exists '*asymmetric* *elasticity*', a condition which can be represented in a simplified way by making a comparison with a vibratory system like that of Fig. 11. In this figure, *m* represents a circular membrane fixed at the edges with in the centre a spring (spring constant *f*), which, at its other end, is firmly fixed; its tension causes the membrane to bulge inwards.

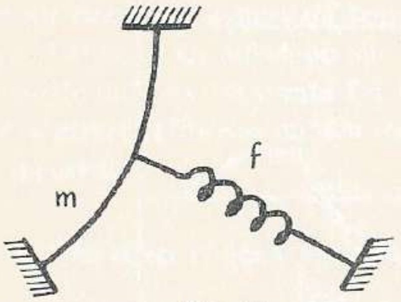

Fig. 11
S ple system with asymmetrical elasticity.

In this situation, the following equation applies:

$$K = f(x) = ax + bx^2,$$

in which K is the repelling force, x the displacement from the equilibrium position and a and b constants. This means that an asymmetric vibratory motion exists as a result of the extra factor bx^2, because, for a negative value of x (deflection in opposite direction) this does not change of sign, thus causing an amplification in a positive direction and an inhibition in a negative direction.

If an external force is allowed to act on such a system, the deflection caused by it will be increased in the direction of the pulling force of the spring and decreased in the opposite direction. The amplitude of the eardrum and of the chain of auditory ossicles and thus the increase of stiffness will therefore be maximal when a positive change of pressure is effected in the auditory canal or a negative one in the tympanic cavity.

This may explain why a positive pressure change in the auditory canal proved to cause a greater threshold loss than a negative change. The correspondence of this detail of the experimental results with the theoretical expectation constitutes a new confirmation of the conception that the effect of pressure change should be attributed to an increase of stiffness of the conduction apparatus.

§ 4. The effect of a positive air pressure change in the tympanic cavity

In the test subjects in whom the effect of pressure change in the auditory canal had been investigated beforehand, the threshold shift for bone and air conduction was determined for a positive change of pressure of 50 cm water brought about in the tympanic cavity.

As in this case the rise of pressure has to be realized via the tuba, no measures to avoid an occlusion effect have to be taken, because the auditory canal need not be closed off.

In contrast to investigations of other authors, a method was followed in which the magnitude of the rise of pressure was known. The test subject was taught to produce a rise of pressure in his tympanic cavity by Valsalva's manoevre. The rise of pressure was measured by connecting one nostril with a manometer. With this method it is possible to maintain a rise of pressure of maximally 50-60 cm water for 30 to 45 seconds, which is sufficient for a reliable determination of the threshold shift.

It is, in reality, the pressure in nose and nasopharynx that is measured by this method, but, as soon as the tuba was opened, this pressure proved to be equal to that in the middle ear. This could be verified by means of the pneumophone.

Fig. 12 represents the threshold shift for bone conduction caused by a positive change of pressure of 50 cm water, brought about in this way in the tympanic cavity.

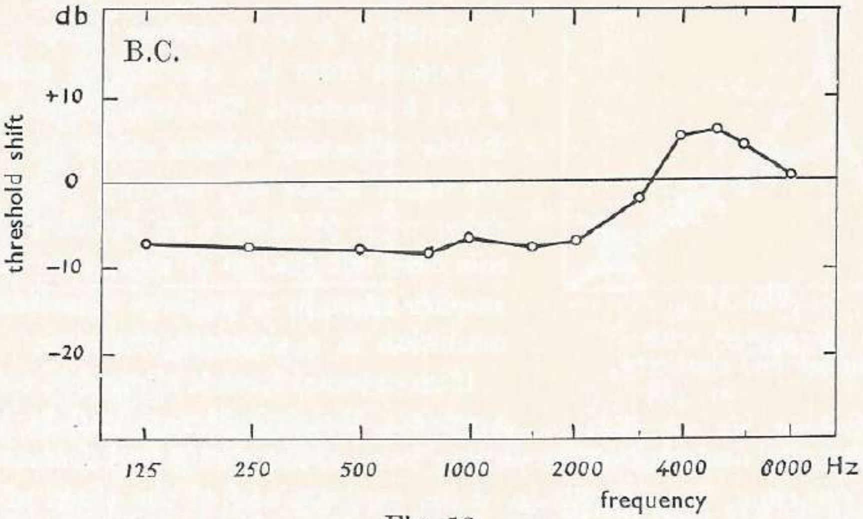

Fig. 12

Threshold shift for bone conduction following a positive change of air pressure of 50 cm water in the tympanic cavity.

The effect proved to be the same as that of an equally great negative change of pressure in the auditory canal. As the auditory canal remains open in these experiments, which means that no occlusion effect can arise, this result confirms the existence of a real effect of air pressure change on bone conduction, as found in § 1 on elimination of the occlusion effect (Fig. 7).

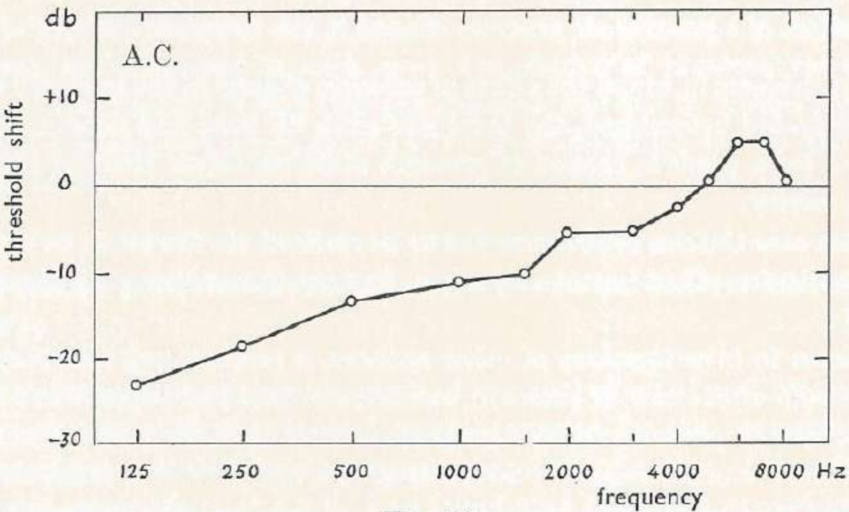

Fig. 13

Threshold shift for air conduction following a positive air pressure change of 50 cm water in the tympanic cavity.

The results of analogous determinations for *air conduction* are shown in Fig. 13. With the exception of a markedly greater effect in the lowest frequencies, here also the same curve was obtained as for an equal negative pressure change in the auditory canal, shown in Fig. 8. We were unable to explain the greater loss found for 125 and 250 Hz.

The results shown in Figs. 12 and 13 also lend support to the idea that the effect of air pressure changes on bone conduction and air conduction should be entirely attributed to an effect on the eardrum and the auditory ossicles. No indications were found —at any rate for frequencies higher than 500 Hz—for the existence of a direct influence on the middle ear via the inner ear windows, as sometimes supposed.

§ 5. The effect of equal positive air pressure changes on both sides of the eardrum

It was finally investigated whether an effect was demonstrable on bone and air conduction hearing by effecting a positive change of pressure of 50 cm water on both sides of the eardrum.

The rise of pressure in the tympanic cavity was brought about via the method described above, and was effected in the auditory canal at the same time. Because now the pressure on both sides of the eardrum remains the same, no influence will be exerted on this membrane. The walls of the tympanic cavity and the cochlear windows are now the only elements that undergo the change of pressure.

It was impossible to demonstrate a threshold shift for bone or air conduction in this experiment. Neither were subjective changes of loudness noticed, at any rate for pressure changes up to + 60 cm water.

It was therefore impossible to demonstrate a change of hearing acuity due to pressure on the inner ear windows alone, which would especially influence the round window.

§ 6. Conclusions; explanation of the effect

The results of our experiments on the effect of pressure changes can be summarized in the following conclusions:

1. Changes of air pressure in the auditory canal or in the tympanic cavity caused a threshold loss both for bone conduction and air conduction, for frequencies lower than 4000 Hz. This loss was greatest in the bass zone with a maximum at about 800 Hz; it gradually decreased for frequencies higher than 1000 Hz. A small threshold gain was found in the area between 4000 and 8000 Hz.

2. The sign and the frequency gradient of the bone conduction threshold shift was similar to that in air conduction, but the shift was half or two-thirds of that in air conduction.

3. The threshold shift was greater for a positive pressure change in the auditory canal than for a negative change.

4. The middle ear apparatus has to be considered the point of action of the effect of air pressure change.

As already remarked by Henrik Johansen in the case of air conduction, the curve of the threshold shift on pressure change corresponds with what might be expected if an increase of stiffness of the ear occurs. The point of action of the pressure change is the middle ear apparatus. Eardrum and auditory ossicles are displaced from their position of equilibrium, which results in an increase of stiffness.

Application of the formula for forced vibrations of a system (see appendix) gives the following formula for the amplitude of the middle ear apparatus:

$$a = \frac{F}{Z}$$

in which $Z = \sqrt{Rm^2 + \left(2\pi f.m - \frac{S}{2\pi f}\right)^2}$ and F represents the force acting on the middle ear.

Increase of the stiffness S of the system will cause an increase of the impedance Z, thus the amplitude a becomes smaller for frequencies lower than the resonance frequency of the system $\left(f < \frac{1}{2\pi}\sqrt{\frac{S}{m}}\right)$. For frequencies higher than the resonance frequency Z will become smaller and a greater. This change of amplitude of the middle ear apparatus, which is theoretically to be expected, is actually found in the threshold shift that occurs on change of pressure for air as well as for bone conduction (assuming that the resonance area of the ear is at about 3000 Hz). The change of vibration of the cochlear fluid may therefore be explained, in both cases, from the increase of stiffness of the middle ear apparatus, the middle ear apparatus and cochlear fluid being regarded as practically one system both in air and bone conduction.

It is a striking feature that this change of the properties of the ossicular-cochlear system in bone conduction has the same effect as regards sign and frequency gradient as in air conduction. This is an argument of favour of the same mode of vibration of ossicular chain and cochlea in the two types of conduction, in spite of the entirely different driving mechanism in the two cases.

The effect of a change of pressure on the sensitivity of bone conduction proves only to be smaller than that on the air conduction sensitivity. This is often regarded in the bone conduction theories as a result of phase differences between the bone conduction stimuli travelling along different pathways.

A more correct approach to the explanation of the difference in magnitude of the effect in bone conduction and in air conduction leads to two possible conclusions, based on the formula $a = \frac{F}{Z}$:

1. A smaller bone conduction effect might arise as a result of a smaller change of impedance Z than is the case in air conduction.

2. The other possible cause of the smaller effect on bone conduction is that in this case the force F acting on the middle ear apparatus, becomes *smaller* due to the change of pressure, the change of impedance being the same as that in air conduction.

re 1. A smaller change of impedance of the ossicular-cochlear system in bone conduction as compared with air conduction would be quite well conceivable, because the driving mechanism of this system differs in the two cases. In comparing the two pairs of curves in Figs 7 and 8 there appears a striking resemblance in their course. In both cases we find an indication of an effect of antiresonance for frequencies of 500-800 Hz and a resonance phenomenon for 4000-8000 Hz.

In bone conduction the effects are less pronounced than in air conduction while the point of zero effect has somewhat shifted to a lower frequency of about 3000 Hz. These discrepancies lend support to the assumption that a difference exists in air and bone conduction between the physical constants Rm, m and S of the system.

re 2. The other possibility presupposes a weakening of the acting force F on the system. This seems acceptable, because, due to the increase of stiffness of the ossicular chain, the coupling of the latter with the skull will become firmer. Thus the force that gives the chain its relative movement with respect to the skull, will decrease.

The explanation of the fact that a positive change of pressure in the auditory canal causes a greater threshold shift than a negative pressure change, has already been discussed in § 3.

This phenomenon proves to be in harmony with the conclusion that the threshold shift results from an increase of stiffness by displacement of the eardrum and auditory ossicles. As explained before, because of the normal conical position of the eardrum, a force in the direction of the cavum tympani (positive pressure change in the auditory canal) causes a greater displacement than a force in the opposite direction (negative pressure). This greater displacement will cause a larger stiffness increase, resulting in a more marked threshold loss.

§ 7. Clinical use of the effect: test of Gellé

The phenomenon of the decreased auditory acuity on air pressure change has found clinical application in the test of Gellé and the pneumophone. Whereas the clinical value of the pneumophone as a means to diagnose a change of pressure in the middle ear is generally acknowledged, the diagnostic value of the Gellé test has been a subject of discussion right from the beginning.

According to Gellé and various investigators after him, it is possible to confirm a stapedial ankylosis by investigating which effect is exerted on air and bone conduction by an increase of pressure in the auditory canal, because, in the case of a stapes fixation, a rise of pressure would not cause a decrease of loudness for bone conduction, whereas it would do so for air conduction (negative Gellé).

In recent years the interest for this method of examination has revived, in association with the development of surgical treatment of otosclerosis. Various authors have tried to obtain pre-operative data regarding the degree of stapes fixation, by quantitative performance of the test. Such investigations were carried out bij Thullen (1954) and by Dudok de Wit and van Dishoeck (1959). In his investigation Thullen confirmed Gellé's findings that in clinical otosclerosis no effect on bone conduction is present, while the effect on air conduction is preserved.

Dudok de Wit and van Dishoeck, on the other hand, found, with their accurate method, a decrease of the effect in otosclerosis, both for air conduction and bone conduction.

In this paragraph the theoretical background of the test of Gellé is discussed, following which a new simple method for quantitative Gellé determinations is described, together with some results obtained by it.

a. Theoretical background of the test of Gellé. The otosclerosis test described by Gellé was based on his 'inner ear explanation' of the effect of air pressure change. At present, however, this theory has almost entirely been abandoned. Remarkably enough, the original set-up of the test of Gellé as a diagnostic method for stapes fixation has been preserved. It is therefore necessary to revise the theoretical background of this method on the basis of the results described in the preceding paragraphs.

As mentioned before, in the normal ear the conduction apparatus is forced out of its normal position by a change of pressure, due to which the stiffness of this apparatus increases, resulting in a threshold loss in the low frequencies both for air and bone conduction. A quantitative performance of the test of Gellé enables us therefore to determine the magnitude of this threshold loss for a given frequency. It is to be expected that no normal results are to be obtained if the conduction apparatus has undergone pathological changes.

1. In the first place, a smaller loss will be measured in the case of decreased mobility of the eardrum and the ossicular chain, because, on change of pressure, its stiffness increases less than normally. This may occur after recurrent otitis media or after recurrent tubal catarrh. No effect of pressure change will be found if the eardrum can not be displaced, like in the case of a perforated or an adhesive eardrum.

2. In the second place, a change in the middle ear may cause a change of the effect exerted on the perception by a certain increase of stiffness. For example, in a stapes fixation the stiffness increase will probably cause a smaller loss than normally, because, due to a diminished coupling between ossicular chain and cochlear fluid, less influence is exerted on perception.

3. Finally, the effect of increase of stiffness also changes if one of the other properties of the conductive apparatus, for example its mass, is modified which can occur due to pathological processes. As has been found in our experiments—Chapter IV, § 3—the effect of air pressure change becomes greatly changed when the eardrum is loaded.

We may conclude that the Gellé test enables us to measure the *degree of mobility* (= increase of stiffness present) of the conduction apparatus, and the effect of a further *increase of stiffness on hearing acuity*. A decrease of the effect of a pressure change is therefore not specific for otosclerosis. A smaller effect may be found in other forms of conductive deafness as well.

As seen above, both air and bone conduction thresholds are normally influenced in the same direction by change of pressure. Thus it is probable that also a decrease of the bone conduction effect exists if the effect on the air conduction diminishes. Only in the case of a change of the conduction apparatus by which air and bone conduction are influenced in different ways (like by increase of mass and by stapes fixation), are differences to be expected, at any rate theoretically.

b. Personal method for quantitative Gellé measurements. The most current way to carry out a quantitative Gellé test is determination of the threshold loss caused by producing a certain change of pressure. Thullen used another method, in which he measured the change of pressure required to make a tone of 5 db above threshold fade away. Both methods are however to be considered insufficiently accurate as a quantitative method to determine relatively small effects of 0-15 db, unless the threshold measurements can be done in a very exact way, like in Dudok de Wit's investigations. This author made his threshold determinations with the audiometer of von Békésy, which method however has the disadvantage of requiring an extensive equipment.

Personal method. A simple and reliable quantitative examination with the test of Gellé is possible by determining the threshold loss as a function of the change of pressure as described in § 2. This only requires the use of an audiometer (preferably with attenuator in steps of less than 5 db) and a pneumophone.

Fig. 14 shows the average result of such a measurement in normally hearing persons for air conduction, positive change of pressure and a frequency of 500 Hz. Such a 'quantitative Gellé curve' is made by investigating which change of pressure is exactly necessary and sufficient to make the perception of a tone of a given intensity above threshold disappear. In this case intensities of 5, 8, 10, 20 and 25 db were chosen. In general 3 or 4 measuring points per curve are sufficient, provided they are well-chosen. Because, by means of the Politzer balloon of the pneumophone, the pressure change can be changed continuously, it is possible to determine rapidly for which pressure the tone becomes just inaudible or is just perceived again. The method offers the best results if the conditions are chosen in such a way that the threshold shift is maximal for the normal ear. This implies that the determinations should preferably be carried out for air conduction, positive pressure change and a low frequency (e.g., 500 Hz).

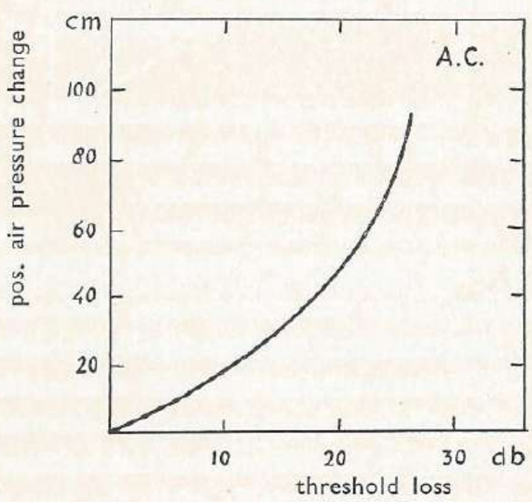

Fig. 14
Quantitive Gellé curve for the normal ear.

c. Some results. The method described was used to carry out quantitative Gellé determinations in patients with different forms of conductive deafness.

1. *Otosclerosis.* The findings of Dudok de Wit and van Dishoeck in patients with otosclerosis were confirmed. The effect of a change of pressure on air conduction had decreased in general moderately to markedly.

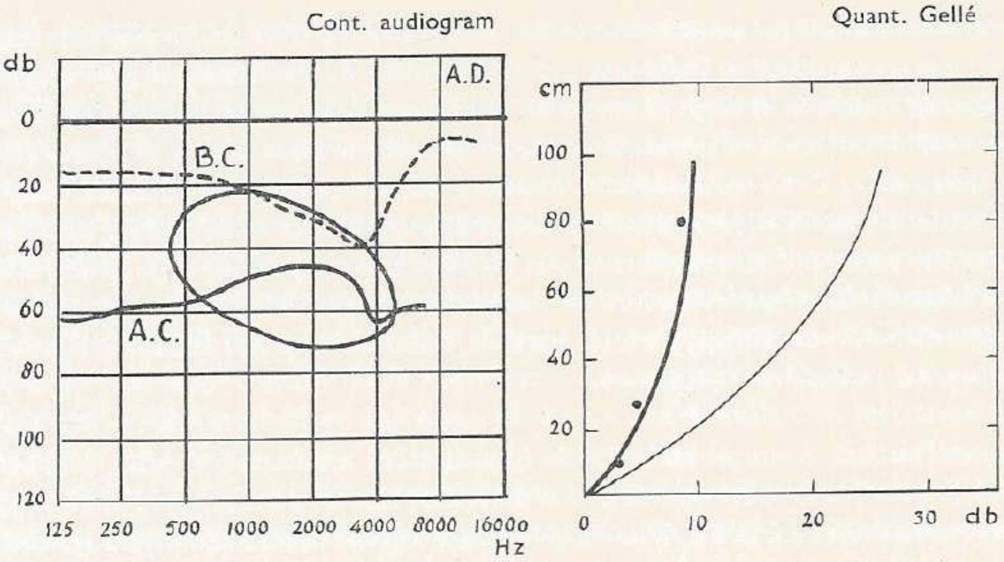

Fig. 15

Continuous audiogram and quantitative Gellé curve in a patient with otosclerosis: decreased effect of air pressure change.

Fig. 15 shows a typical example of this. It represents an audiogram and Gellé curve of a patient with otosclerosis. In otosclerosis the Gellé curve takes a steeper course than normally.

According to most authors (e.g., Gellé, Thullen, Rasmussen) clinical otosclerosis is characterized by a *negative* Gellé which means: no effect on bone conduction following air pressure change, while the effect on air conduction is preserved.

The results of our investigations—like those of Dudok de Wit and van Dishoeck—indicate a marked decrease of the effect on air conduction, as well as a decrease of the effect on bone conduction. In our opinion, the results of the other authors are probably to be attributed to the fact that, in spite of its decrease, the air conduction effect is still perceptible, while the bone conduction effect is difficult to demonstrate if it becomes still smaller.

The cause of the decrease of the threshold loss due to change of pressure in otosclerosis should probably especially be sought for in the diminished coupling between middle ear and cochlea, due to which changes in the middle ear exert less influence on the perception. This is also evident from the absence of the occlusion effect and the effect of loading of the eardrum on bone conduction in otosclerosis. A reduction of the mobility of the conduction apparatus, as thought by Gellé, seems a less important factor. It is even acceptable that in otosclerosis the eardrum is actually stronger bent through under the influence of the pressure change than normally, now that the ossicular chain can give less way due to the stapes fixation.

2. *Conduction deafness of other origin.* As said in the theoretical introduction, in many cases of conductive impairment with another aetiology than otosclerosis, a decrease of the effect of a pressure change on the auditory acuity is to be expected.

Gellé curves were therefore also determined in patients with a conduction deafness of other cause.

A *decrease* of the effect, i.e., a steeper curve as found in otosclerosis, was also present in many cases of conduction deafness due to previously sustained otitis media or tubotympanitis. This is understandable, because in general inflammatory processes will lead to a greater rigidity of the conduction apparatus.

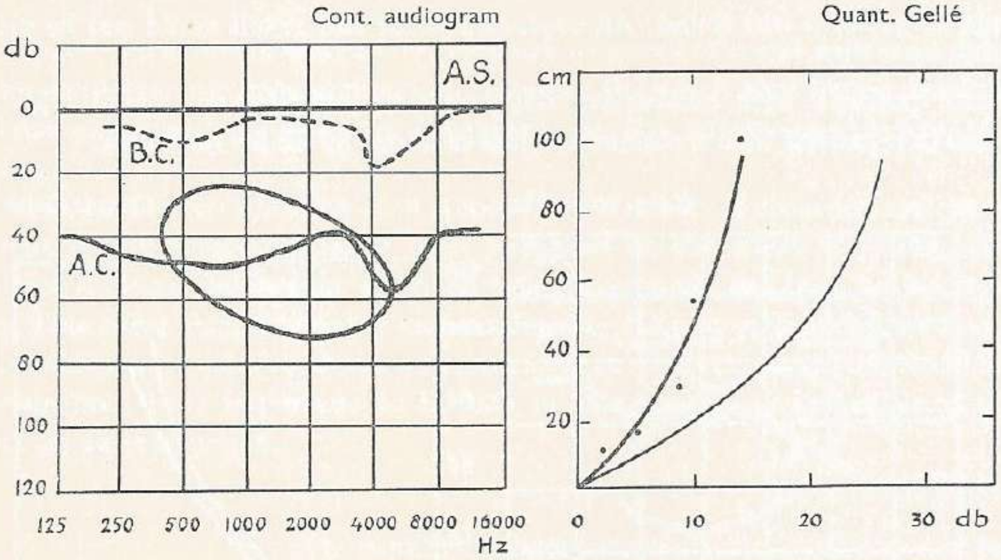

Fig. 16
Continuous audiogram and quantitative Gellé curve in a patient with conduction deafness caused by chronic otitis media. The effect of air pressure change is diminished.

Fig. 16 gives as an example the audiogram and the Gellé curve of a patient with a conductive loss caused by recurrent otitis media. The highest decrease of the effect of a pressure change was usually found in patients with the greatest hearing losses. In some cases, however, such a correlation was not found.

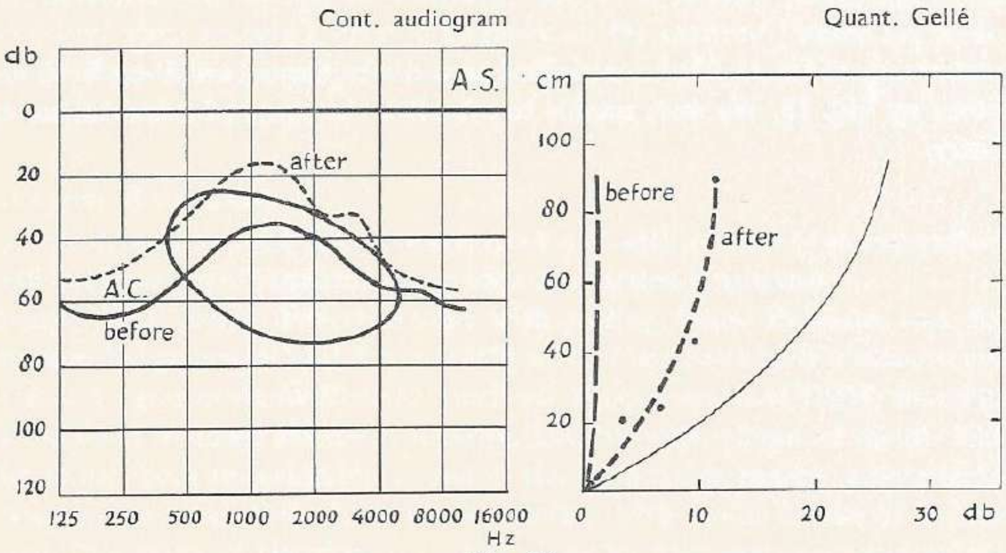

Fig. 17
Continuous audiograms and quantitative Gellé curves in a patient with retracted, adhesive eardrum before and after treatment.

According to expectations, *no effect* was found in the cases with a markedly retracted eardrum, an adhesive eardrum or a perforated eardrum.
Fig. 17 shows the audiogram of the left ear of a patient with bilateral retracted and adhesive eardrums. No effect of change of pressure was demonstrated in this case. A marked hearing improvement was obtained by treatment of the Eustachean tubes, following which pressure change proved to exert a small effect. In contrast to expectations in some patients with a perforated eardrum a slight influence of change of pressure was found. An explanation for this result could not be given.

In some patients with conductive deafness a *normal effect* was found. This was the case in a patient with a conduction loss of about 50 db for both ears.

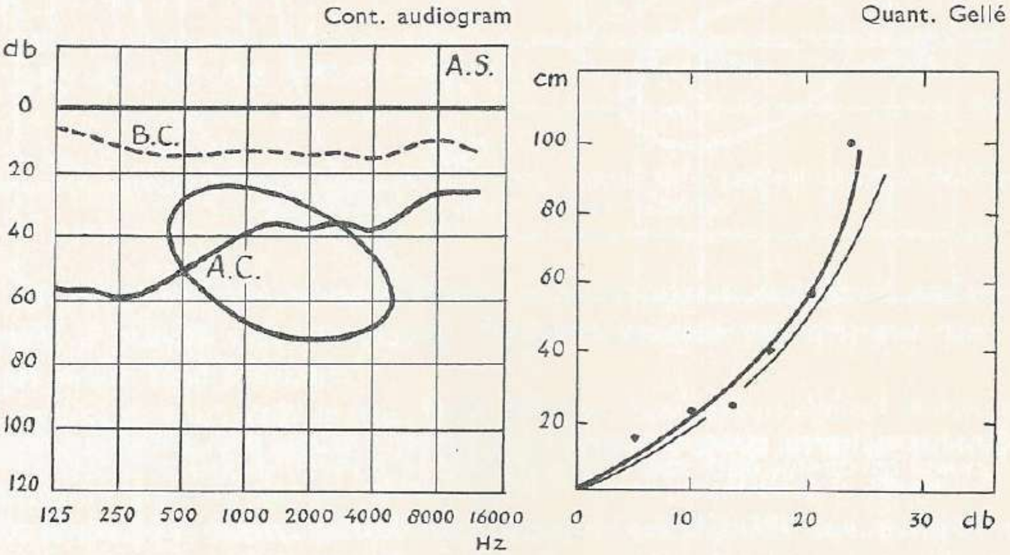

Fig. 18

Continuous audiogram and normal quantitative Gellé curve in a patient with conduction deafness of unknown aetiology.

Determination of the Gellé curve yielded an entirely normal result on both sides, as shown by Fig. 18. We were unable to establish the cause of this deafness with certainty.

CHAPTER III

THE EFFECT OF LOADING OF THE EARDRUM

Loading of the eardrum with water, mercury or pieces of metal causes an increase of the sensitivity for bone conduction, whereas the sensitivity for air conduction remains unchanged or decreases dependent on the nature and degree of the loading.

In contrast to the situation with respect to the effects of occlusion and pressure change, few investigations have been published on the effect of loading of the eardrum on bone conduction, although this phenomenon has been known equally long. This effect should however be considered equally important for the study of the mechanism of bone conduction hearing. When studying this bone conduction phenomenon, it is important to include in this case too an investigation of the effect on air conduction.

I. FORMER INVESTIGATIONS

History

The first description of the effect of loading of the eardrum on bone conduction was given by Wheatstone (1827). In his publication mentioned before, in which he deals with the occlusion effect and the effect of pressure change, Wheatstone described that, on filling of the auditory canal with water, a bone conduction tone becomes louder and is lateralized in the ear involved. Various investigators after him have made the same observation and have also attempted to explain it (Politzer, Schmiedekan, Lucae, Kretschman). Later R. Bárány (1910) did a similar observation when placing a drop of mercury on the eardrum, which led to an increase of the auditory acuity for bone conduction, while that for air conduction remained almost unchanged.

Measurements of the effect

Only few determinations have been carried out with respect to the magnitude of the effect of loading of the eardrum on bone conduction sensitivity.

Runge (1923) made determinations with tuning forks, Pohlman and Kranz (1926) and Zangemeister and Kietz (1953) carried out audiometric measurements. They found a gain of about 10 db for the lower frequencies. Sato (1956) found a fall of threshold of 30 db for low frequencies on loading with pieces of metal. Kirikae (1959) found, both in test subjects and in the animal experiment, a gain of 25 db for frequencies lower than 2000 Hz on loading with metal blocks of a mass of 200 mg. The curve of the threshold shift given by him contained various peaks, the most important of which were situated at frequencies of 300 and 900 Hz. On loading with a smaller mass these peaks were found at higher frequencies.

Explanation

The explanation of the bone conduction gain was sought by Runge (1923) and Sato (1956) in an increase of the osteotympanic bone conduction route, because, due to the loading, there would be a greater sound energy transfer from the bone to the eardrum.

Krainz (1926) observed in his experiments that on loading of the eardrum the vibratory amplitude of the auditory ossicles increases, while its phase lag with respect to the skull diminishes. Due to these two changes, the contribution of the middle ear to bone conduction would increase, which according to this author explains the threshold gain found.

The explanation given by E. Bárány (1938, 1940) is related with this conception. According to this author, loading of the eardrum causes an increase of the 'inertia oscillations' of the auditory ossicles, as the centre of gravity of the ossicular chain moves to a greater distance from its rotation axis. This results in an increase of the 'inertia bone conduction', which Bárány, in view of his experiments, considers the most important mechanism by which bone conduction hearing develops for low frequencies.

Clinical application

Clinical application of the effect of loading on bone conduction was described by Runge in 1923; he observed that filling of the auditory canal with water did not cause an increase of loudness for bone conduction in patients with a conduction deafness. This simple examination might therefore serve as a diagnostic aid.

The test of Runge has however found little application, as shown by the absence of further publications on it. Only Zangemeister and Kietz (1953) mentioned this test as a diagnostic aid for otosclerosis.

Effect on air conduction

Investigations into the influence of eardrum loading on air conduction perception were carried out first by Fowler sr (1928) and subsequently by Lüscher (1939, 1945), who described the development of a bass deafness. Van Dishoeck and de Wit (1944) determined the threshold shift on loading with different amounts of water, mercury and oil. On slight loading they only found a loss in the high tones, increasing with rising frequency, while on loading with a greater mass a considerable threshold loss was found in the lower frequencies as well. Kirikae (1959), on the other hand, described in his experiments, in which a loading mass of 200 mg was used, only a small air conduction loss in the lower frequencies.

An explanation of the high tone loss, as found by van Dishoeck and de Wit is, according to Henrik Johansen (1948), in agreement with what is to be expected on the strenght of the impedance formula $Z = \sqrt{Rm^2 + \left(2\pi f.m - \frac{S}{2\pi f}\right)^2}$.
An increase of the mass m, says Johansen, leads to an increase of the impedance, which is the higher the greater the rise of the frequency f. The resonance point of the ear will shift to a lower frequency, which means that, theoretically, a gain would have to be found for the low frequencies. That this is not the case should, according to this author, be attributed to the fact that loading does not cause a pure increase of mass but also a greater stiffness.

§ 1. The threshold shift for bone conduction following loading of the eardrum as a function of frequency

The threshold shift for bone conduction as a function of the frequency was determined in 6 persons with normal hearing on loading of the eardrum with 200 mg water and 200 mg mercury.

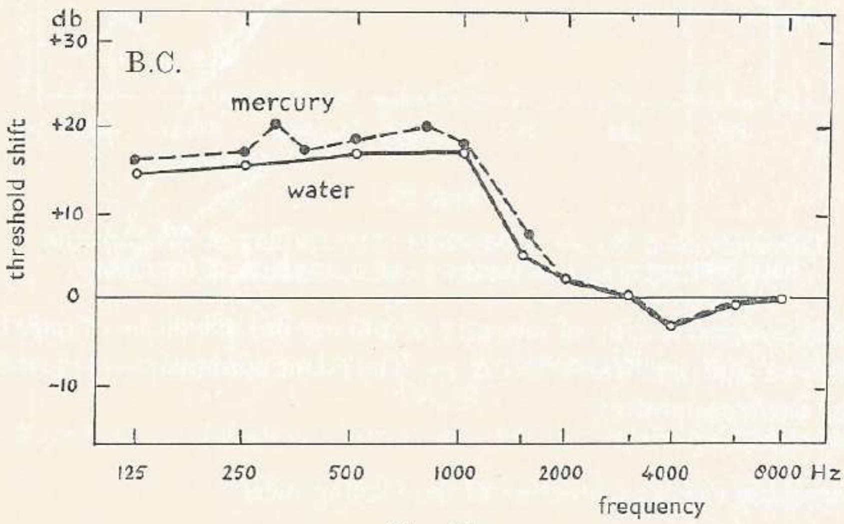

Fig. 19

Threshold shift for bone conduction following loading of the eardrum with 200 mg water or mercury as a function of frequency.

As shown by Fig. 19, a threshold gain of 15-20 db was found for frequencies up to 1000 Hz both for loading with water and with mercury. This gain decreases gradually for higher frequencies, while for frequencies above 2000 Hz a manifest effect is no longer to be demonstrated, with the exception of 4000 Hz where sometimes a slight rise of threshold was measured. As regards its magnitude, the threshold gain found is intermediate between the results of other authors. The course of the curve agrees rather well with the audiogram found by Zangemeister and Kietz on filling of the auditory canal with water. The existence of peaks in the curve of the threshold shift, as described by Kirikae, was sometimes confirmed, although they were not found in the same number and of the same degree.

For *air conduction*, a great difference was found between the effect of water loading and mercury loading. While, as shown in Fig. 20, on loading of the eardrum with 200 mg water a great loss was measured in the higher frequencies—increasing with frequency—no such effect was observed on loading with 200 mg mercury. The loss in high tones described by van Dishoeck and de Wit was therefore confirmed for loading with water only.

It is acceptable that the difference in effect of loading with the same mass of water or mercury, as found in the experiment, is caused by the difference in volume

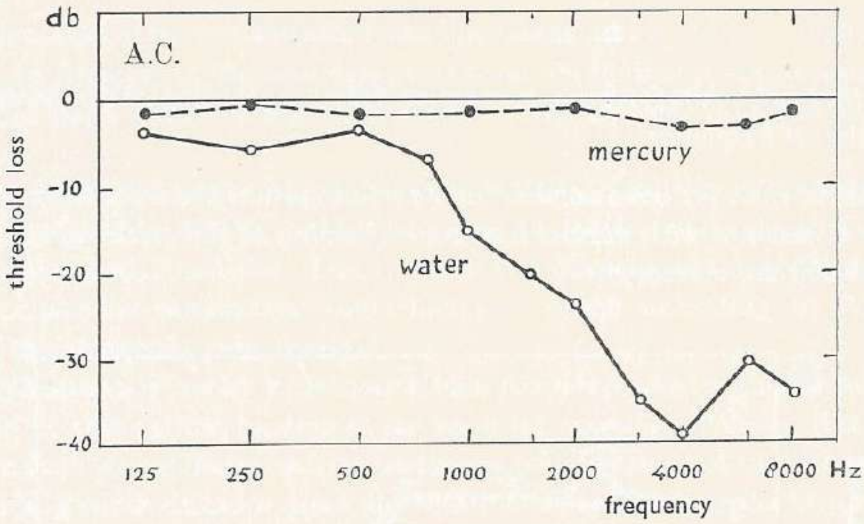

Fig. 20

Threshold shift for air conduction after loading of the eardrum with 200 mg water or mercury, as a function of frequency.

of the loading masses: a drop of mercury of 200 mg has a volume of only 0.015 ml, whereas that of 200 mg water is 0.2 ml. The latter amount proves just sufficient to cover the eardrum entirely.

§ 2. The threshold shift as a function of the loading mass

The magnitude of the threshold shift caused by loading of the eardrum depends on the amount of the loading mass. This dependence was investigated for a low and a high frequency.

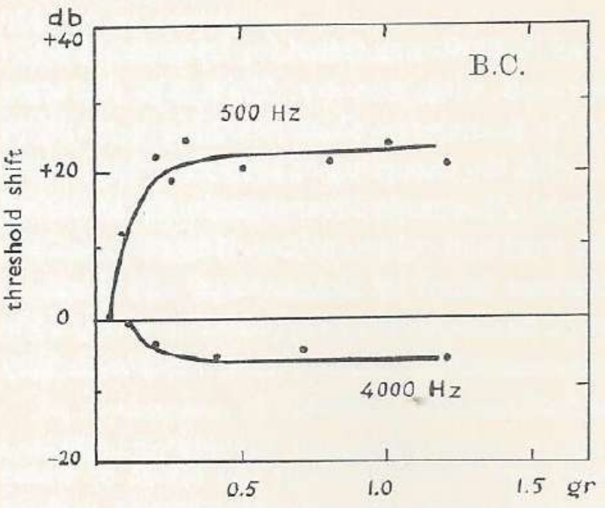

Fig. 21

Threshold gain for bone conduction as a function of the loading mass.

Fig. 21 shows the curve of the threshold shift for bone conduction as a function of the loading mass, for frequencies of 500 and 4000 Hz. It was shown, both for loading with water and mercury, that there is a marked effect even for slight loading and that a maximum value of 20-25 db is reached for a loading mass of about 250 mg. On further increase of the loading, up to filling of the auditory canal (i.e., for water a mass of about 1200 mg and for mercury of about 15.3 g), this gain remained unchanged.

For air conduction the course of the curves found on water and mercury was different (Fig. 22).

For high frequencies, for example of 4000 Hz, loading with water, even to a slight degree, caused a manifest loss. On increase of the load this loss became linearly greater up to a value of about 30 db, following which the graph curves and the effect of greater loading diminishes gradually. For the low frequencies, a load of at

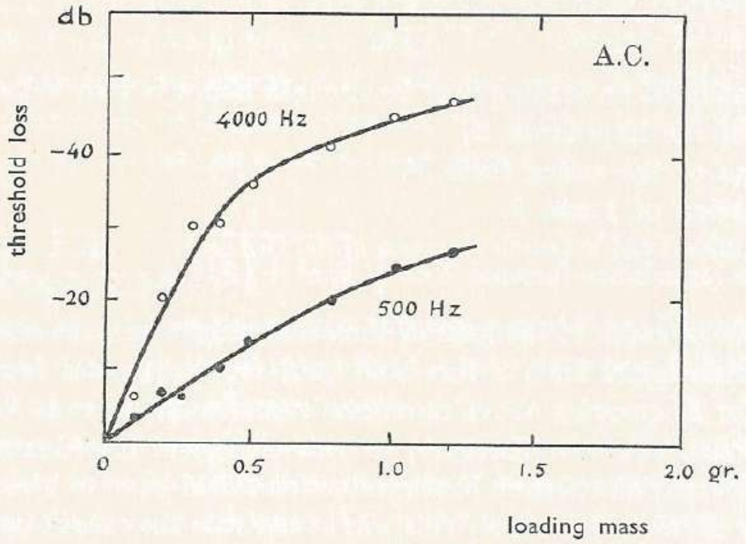

Fig. 22

Threshold loss for air conduction as a function of the loading mass.

least some hundreds of milligrammes was required before there was a measurable effect. This increased almost linearly on greater loading.

Loading with mercury also did not cause a clearly demonstrable threshold loss until the loading mass exceeded about 500 mg. Here also the loss was greatest for the high frequencies. Further increase of the loading mass caused a gradual augmentation of the effect, until here also a saturation effect developed.

§ 3. Conclusions; explanation of the effect

The results of the experiments described can be summarized in the following conclusions:

1. Loading of the eardrum caused a threshold gain for bone conduction of 20 db for frequencies up to 1000 Hz. For higher frequencies this gain diminished and no effect occurred above 2000 Hz.
2. This threshold gain for bone conduction reached its maximum for loading with a mass of 300-500 mg. A further increase of the loading mass did not exert any influence. It did not matter whether water or mercury was used.
3. The air conduction threshold was not influenced on loading with small amounts of mercury (100-800 mg). The same mass of water, or a greater mass of mercury ($>$ 1000 mg) caused considerable losses in the high tone region, the stronger the higher the frequency. Increase of the loading mass made these losses greater and also caused a reduction of the sensitivity for low frequencies.

Loading of the eardrum thus causes an increase of the bone conduction sensitivity for the low and the middle frequencies. This implies that an increase of amplitude of the vibration of the ossicular-cochlear system has occurred. Application of the formula for the forced vibration to this system, gives for ist amplitude:

$$a = \frac{F}{Z}.$$

The increase of amplitude on loading may be brought about in two ways:

1. by decrease of the impedance Z,
2. by an increase of the acting force F.
3. by a combination of 1 and 2.

re 1. Based on the impedance formula $Z = \sqrt{Rm^2 + \left(2\pi f.m - \frac{S}{2\pi f}\right)}$, a decrease of Z below 1500 Hz as cause of the gain of threshold, might be attributed to an increase of the mass. Apart from a threshold gain for frequencies lower than resonance, a loss for frequencies above resonance values would have to be found. This was not the case, however. Moreover, on this change of impedance due to increase of mass, not only an effect on bone conduction would have to be expected, but also an effect on air conduction. This was at any rate the case in impedance changes caused by increase of stiffness. However, eardrum loading with 200 mg mercury did not influence the air conduction threshold. Only if the eardrum was covered by the loading mass did an effect on air conduction arise.

In view of this, it seems incorrect to explain the bone conduction threshold gain after loading, from a change of impedance by increase of mass, as done by Henrik Johansen with respect to the effect on air conduction.

Results of the experiments described in § 3 of Chapter IV, however, pleaded exactly for an effect of increase of mass, as they indicated that eardrum loading caused a lowering of the resonance area of the ear, which has to be attributed to an increase of mass $\left(f_{res.} = \frac{1}{2\pi}\sqrt{\frac{S}{m}}\right)$.

re 2. An increase of the force acting on the middle ear apparatus seems theoretically more probable. The mass lying on the eardrum will, like the auditory ossicles, perform a vibratory motion with respect to the skull as a result of its inertia. This vibration will be imparted to the eardrum, which results in an increase of the force acting on the auditory ossicles.

$$F_{total} = F_{chain} + k.\ F_{loading\ mass}$$

in which F depends on the inertia moment of these masses.

Both forces are probably not entirely in phase, and it is therefore not allowed merely to add them up.

Although an increase of F on loading seems acceptable, this does not explain why the gain of threshold only occurs for frequencies lower than 2500 Hz. It is however of importance to remark that the same frequency gradient was found for the threshold gain on occlusion. This effect could also be attributed to an increase of the force acting on the middle ear as we have seen.

Apparently this supposed increase of F takes only place below 2500 Hz, or—and this is more probable—its increase has no effect on the cochlear vibration at higher frequencies. The latter is in agreement with the fact that for high frequencies the skull does not vibrate as a whole, but that it undergoes deformations with compression and expansion. With such a complicated mode of vibration various parts of the skull will move in opposite phase. It is therefore to be expected that the relative vibratory movement of the ossicular chain is smaller. The ossicles should therefore probably no longer be regarded as a driving part of the ossicular-cochlear system, or at any rate to a much lesser degree.

For *air conduction* a threshold shift was only found if the loading mass covered the eardrum almost entirely.

The loss of high tones caused by this was regarded by Johansen as a result of an increase of mass. As F will be constant in air conduction, the threshold shift must be based on a change of impedance.

However, the threshold loss found on loading with 200 mg water for example, cannot only be explained from an increase of mass, as can be found by calculation. Moreover, for frequencies lower than resonance, a loss is found instead of the gain to be expected for an increase of mass. According to Johansen, this loss occurs because loading also increases the stiffness. Our results lend support to this supposition, as for 6000 Hz a smaller loss was found than at 4000 and 8000 Hz. This might be an effect of stiffness, because increase of stiffness causes a gain of threshold at this frequency (Fig. 8). An important cause for the loss of low tones on loading seems, however, the development of an *increased resistance*. This would also explain the great loss in the high frequencies, which is not sufficiently accounted for by increase of mass alone, as increase of resistance implies a loss for all frequencies.

That the air conduction sensitivity is influenced by loading of the eardrum with 200 mg water, while there is no influence on loading with 200 mg mercury, should be attributed to the difference in volume of the loading mass.

The absence of an effect on loading with a drop of mercury (200 mg = 0.015 ml) means that this drop does not form part of the conduction apparatus. It is understandable that this is otherwise with a load that covers the whole eardrum. The conduction apparatus is now set in vibration via the loading mass.

In bone conduction, on the other hand, it makes no difference whether the eardrum is covered or not by the loading mass, because here it is only the mass of the loading that is relevant.

§ 4. Clinical use of the effect: test of Runge

Although the clinical investigation of the effect of loading on bone conduction according to the method described by Runge is a simple procedure, this test has found little practical application. This is no doubt due to the fact that, since its discovery, there has been little need for a new means of differentiation between conduction and perception deafness. From the theoretical point of view, however, quantitative performance of this test should yield as many data about the conduction mechanism as the test of Gellé. The difficulties involved in the execution of a quantitative examination, and the circumstance that loading does not cause a pure increase of mass, reduce the usefulness of this test, however.

CHAPTER IV

COMBINED EFFECTS OF OCCLUSION, CHANGE OF AIR PRESSURE AND LOADING

The experimental bone conduction effects studied: occlusion of the meatus, change of air pressure and loading of the eardrum, may also be produced in combinations. An investigation into the effect of such combinations on bone conduction perception is not known in the literature. Its study is however as important as that of the individual phenomena, because, under pathological circumstances, in a great many cases a combination of changes in the properties of the hearing organ is involved.

This chapter describes the results of experiments in 5 test subjects with normal hearing.

§ 1. Combined effects of occlusion and change of air pressure

Occlusion of the auditory canal and change of pressure may be combined in various ways. It is possible to produce a change of pressure in the cavum tympani during occlusion (personal method described on page 25) or in the external auditory canal (personal method described on page 21). Conversely, occlusion may be caused after preceding production of a change of pressure by one of the methods mentioned. To study the combined effect of occlusion and change of air pressure, in the present case the change of pressure in the auditory canal was effected during occlusion of the meatal opening. The results were checked with one of the other methods.

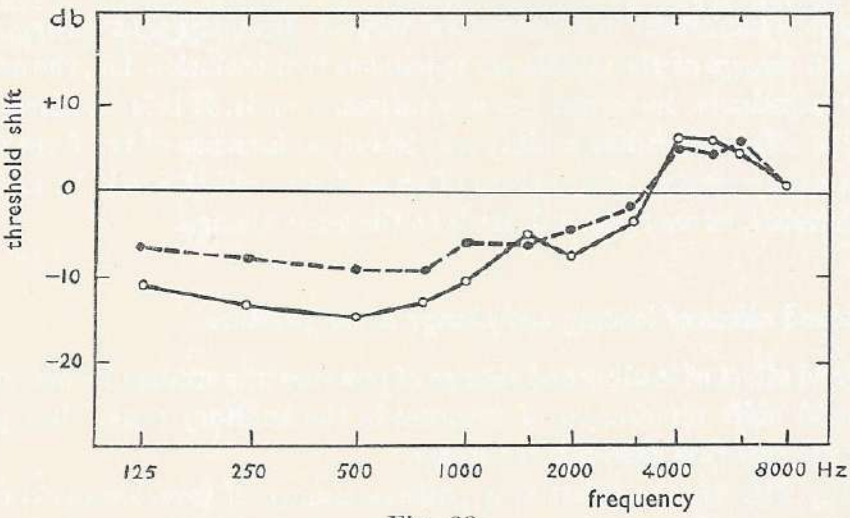

Fig. 23

Threshold shift for bone conduction following a positive air pressure change of 50 cm water during occlusion of the meatal opening (solid curve), compared with that with open ear (dotted curve).

Fig. 23 shows the effect of a positive pressure change of 50 cm water during occlusion of the meatal opening in comparison with the effect with open auditory canal. During occlusion the threshold shift proves to be qualitatively the same, but quantitatively greater than with open auditory canal. This is understandable in the light of our earlier conclusions.

As indicated in Chapter I, occlusion of the meatal opening means that an air column with a greater impedance than the ambient air is coupled to the ear. This causes a decrease of the energy uptake by the external ear as a result of which the the force acting on the middle ear apparatus becomes greater. The vibratory amplitude of the middle ear will therefore be greater and a threshold gain occurs.

Change of pressure on the other hand increases the impedance Z—at any rate for frequencies lower than 4000 Hz—by increase of stiffness which causes a reduction of the amplitude of the middle ear vibrations.

As follows from the formula $a = \frac{F}{Z}$, this diminution of amplitude due to the increase of Z, will be greater the stronger the force F.

Thus on occlusion a greater effect of pressure change is to be expected than with open meatus, and this was actually found.

§ 2. Combined effect of loading and occlusion

The effect of combination of loading and occlusion on the bone conduction threshold was studied by determining the threshold shift on occlusion of the meatal opening after preceding loading of the eardrum with 200 mg water or mercury.

During the loading an occlusion effect was no longer to be demonstrated, nor if the occlusion was brought about at other distances from the eardrum. The threshold gain of 20 db for the lower and middle frequencies, caused by loading, persisted unchanged.

This result is important in a theoretical respect. It means that eardrum loading causes such a change of the middle ear apparatus that occlusion, i.e., the adaptation of another impedance, no longer has any influence on it. If it is assumed (Chapter III) that the effect of loading mainly consists of an increase of the force acting on the middle ear apparatus, the absence of an occlusion effect would be understandable, as occlusion, as we supposed, leads to the same change.

§ 3. Combined effect of loading and change of air pressure

The combined effect of loading and change of pressure was studied by determinating the threshold shift on change of pressure in the auditory canal after preceding loading of the eardrum with 200 mg water.

As shown by Fig. 24, the effect of a positive change of pressure of 50 cm water during loading with 200 mg differed considerable from the effect on the normal ear. A threshold loss arose up to 400 Hz, instead of up to 3000 Hz, while a threshold gain was found for frequencies of 500-2000 Hz instead of 4000-8000 Hz.

This change of the threshold shift can be explained by the assumption that

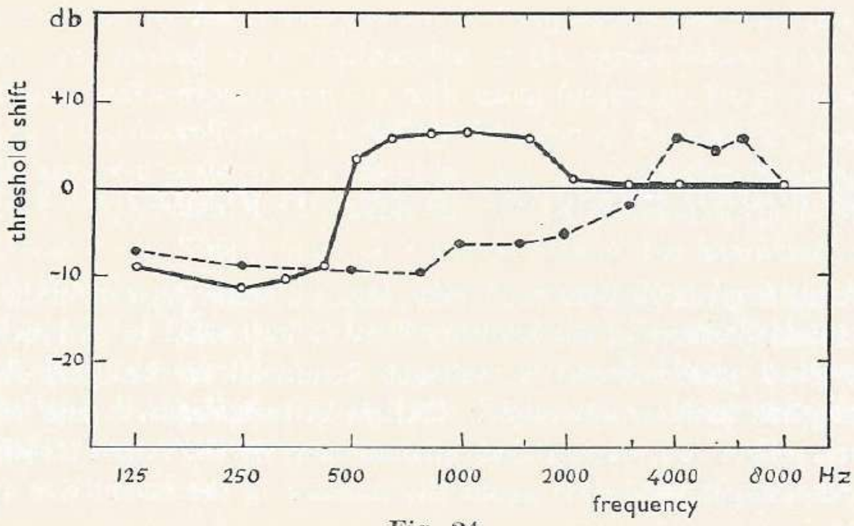

Fig. 24

Threshold shift for bone conduction following a positive air pressure change of 50 cm water after loading of the eardrum with 200 mg (solid curve), compared with that in the normal ear (dotted curve).

loading causes an increase of mass, as such greater mass causes a lowering of the resonance frequency of a vibratory system, as follows from the formula

$$f_{res.} = \frac{1}{2\pi}\sqrt{\frac{S}{m}}.$$

Quadruplication of the mass reduces the resonance frequency by half. As found in Chapter II, change of pressure causes, by increase of the stiffness, a threshold loss below resonance and a threshold gain above resonance. If the mass is increased the curve of the threshold shift therefore has to show a 'displacement to the left' with respect to normal, because the resonance area of the ear is lowered. This was indeed found, as shown in Fig. 24.

CHAPTER V

THE SOUND PRESSURE IN THE AUDITORY CANAL

A sound stimulus given via bone conduction causes a sound pressure in the external ear. This sound pressure in the auditory canal is important in various respects.

In theoretical publications it is thought significant for bringing about the sound perception in bone conduction. Clinical investigations, former as well as recent ones, reflect the opinion that measurement of the sound pressure in the auditory canal might yield data about the function of the conductive apparatus of the ear.

I. FORMER INVESTIGATIONS

History

The first investigations regarding the sound pressure in the auditory canal in bone conduction were carried out by Mach (1863), who spoke of the 'Schallabfluss' from the meatus. As described elsewhere, Mach assumed that in bone conduction sound energy flows in an outward direction from the skull via cochlea, middle ear and auditory canal, and that bone conduction perception increases by an impediment of this 'Schallabfluss'

Politzer (1864), Lucae (1864) and Jankau (1892) tried to verify Mach's theory. In patients with an asymmetric deafness they investigated, by means of a stethoscope, whether there existed a difference in 'Schallabfluss' between the two ears, as this would afford a basis for the differentiation between conduction and perception deafness. However, the results were variable and conflicting, which made that this method was not accepted for clinical use at the time.

Measurements of the sound pressure

In later years Mach's ideas were supported by Claus (1909) and Tondorf (1924) on the basis of the results of their measurements of the sound pressure.

Kley (1952) also considered the results of his investigation a support for this theory. He found that in patients with a unilateral conduction deafness the 'Schallabfluss' from the diseased ear was less than that from the healthy ear. This was observed in all forms of conduction deafness, except in ears that had undergone a radical operation; in these ears an increased 'Schallabfluss' was measured. No important difference was found between the two ears in persons with perception deafness and with normal hearing. Apart from the fact that we regard Mach's theory as obsolete, it remains problematic whether Kley's results really support Mach's ideas, in view of Kley's finding of an increase of the sound pressure in ears subjected to a radical operation, (understandable in view of the large cavity). For this means that on the side of the conduction deafness, the 'Schallabfluss' is greatest, not smallest.

The difference in 'Schallabfluss' between normal ears and ears with a conduction deafness, as found by Kley, was greatest for frequencies less than 1000 Hz. He understood this finding as a confirmation of the earlier 'observation' that the lateralization phenomenon disappears with rising frequency. As example of this he mentioned the lateralization caused by occlusion of the auditory canal. Kley, like Mach, apparently starts from the idea that in conduction disturbances the lateralization phenomenon has the same cause as in occlusion, i.e., an impediment of the 'Schallabfluss'. This is however not true, because the lateralization for low and middle frequencies caused by occlusion can be explained from the threshold gain produced by it. This cannot be the cause in middle ear affections, because here the bone conduction threshold is normal or raised. Moreover, investigation of such patients shows that, though their lateralization impression declines it still persists for high frequencies in most cases.

Clinical use

In recent years various investigators have taken a renewed interest in the old idea, that the function of the conduction apparatus could be determined from the magnitude of the sound pressure in the auditory canal.

Independent of each other, Anderson, Holmgren and Holst (1956), Lundberg (1957) and Holcomb (1959) elaborated a method for this and tested it clinically. Anderson and co-workers found that the sound pressure in an ear with a conduction disturbance is greater, a result opposed to the findings of Kley, which were unknown to them.

Based on his experiments, Holcomb arrived at the conclusion that measurement of the sound pressure is not a suitable method to obtain reliable clinical data.

Origin of the sound pressure

Differences of opinion exist with respect to the way in which the sound pressure arises. According to Mach and the investigators who support his theory, like Kley, the sound pressure in the auditory canal originates from the middle ear. The authors who wish to use this sound pressure as a measure for the function of the conductive apparatus, also apparently start from the supposition that sound energy from the middle ear is the determining factor.

According to von Békésy (1932), on the other hand, the vibrations of the bony wall of the auditory canal and especially the relative vibrations of the capitulum mandibulae with respect to this wall, should be regarded as the cause. He advanced various arguments in favour of his theory:

1. There exists a close relationship between capitulum mandibulae and auditory canal, as shown by the fact that there are clearly perceptible volume changes of the auditory canal on movement of the lower jaw.

2. In bone conduction a phase difference exists between the vibrations of the skull and the lower jaw, resulting in relative movements between the two.

3. If the jaws are firmly clenched together, it is to be expected that these relative movements diminish. That this is indeed the case, follows, according to von Békésy, from the fact that the loudness of the bone conduction tone decreases on closure of the jaws.

This was later confirmed by investigations of Franke and coworkers (1952), who found a decrease of the sound pressure in the auditory canal of 6-10 db for frequencies of up to 700 Hz on closure of the jaws.

II. PERSONAL EXPERIMENTS

METHODS AND APPARATUS

The sound pressure measurements in the auditory canal were carried out at the eardrum with a Bruel and Kjaer audiofrequency spectrometer 2109 and a sound probe made of polyaethylene. Where necessary the results were corrected on the strenght of the frequency characteristics of the probe tube.

§ 1. The sound pressure in the external auditory canal as a function of frequency

In 10 persons with normal hearing the sound pressure in the auditory canal was measured for different frequencies, when a stimulus was given to the homologous mastoid. For this purpose a Peekel audiometer type D 4 was used, the volume control setting of which was fixed at 80 db.

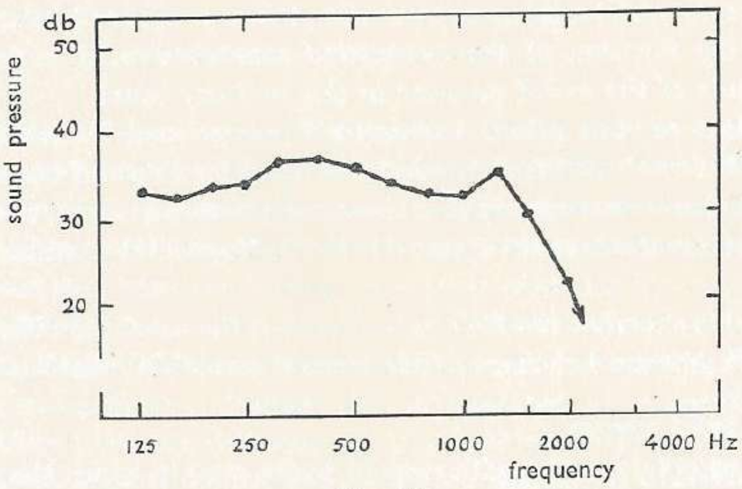

Fig. 25

Sound pressure in the external auditory canal when a bone conduction stimulus of 80 db is given to the homologous mastoid.

For frequencies up to 1200 Hz the sound pressure amounted to 40-30 db, or 10^{-5} -10^{-4} times the stimulus. For higher frequencies the magnitude of the sound pressure declined rapidly, to become unmeasurable at about 2500 Hz (Fig. 25).

As was to be expected in view of individual variations in the shape of the auditory canal, the results obtained sometimes showed wide variations. The differences especially concerned the height of the sound pressure; the course of the curve was in general the same.

It was irrelevant at which place in the auditory canal the measurements were carried out. The values found at the eardrum differed hardly from those measured in the meatal opening.

Fig. 26 shows the sound pressure curve in the auditory canal for a bone conduction stimulus which for all frequencies was 60 db above threshold. The dotted curve indicates the sound pressure which-ceteris paribus-was measured when an air conduction

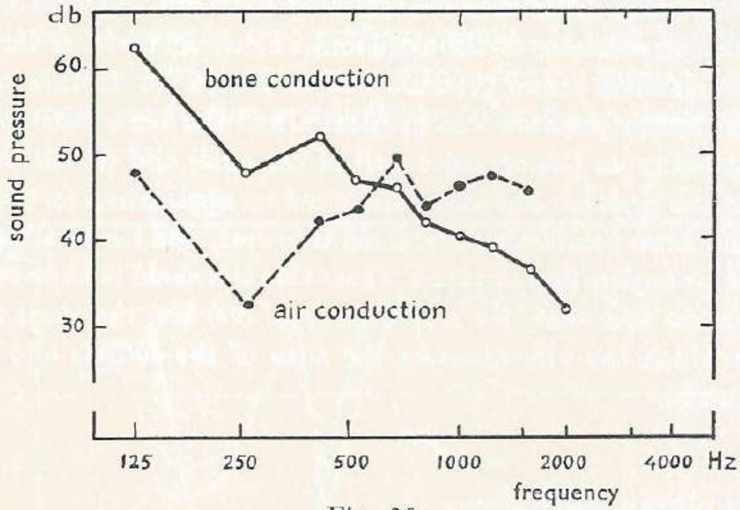

Fig. 26

o———o sound pressure in the auditory canal on a bone conduction stimulus of 60 db above threshold at the mastoid.

•- - - - -• sound pressure in the auditory canal on an air conduction stimulus of 60 db above threshold at the mastoid.

stimulus, also of 60 db above threshold, was given by means of a telephone receiver.

The sound pressure in the auditory canal for bone conduction stimuli on the mastoid is higher for low frequencies and lower for high frequencies than when an air conduction stimulus causing the same sensation is given. This suggests that the sound pressure, which arises in the auditory canal in bone conduction, should—with open meatus—not be considered as a stimulus that brings about the bone conduction via the air conduction route. Previous experiments (Chapter I, § 4) have already shown that such a conception should not be considered correct with closed meatus either.

§ 2. The sound pressure as a function of the place of application of the bone conduction stimulus for low frequencies

The value of the sound pressure in the auditory canal for bone conduction depends on the place on the skull where the sound impulse is given.

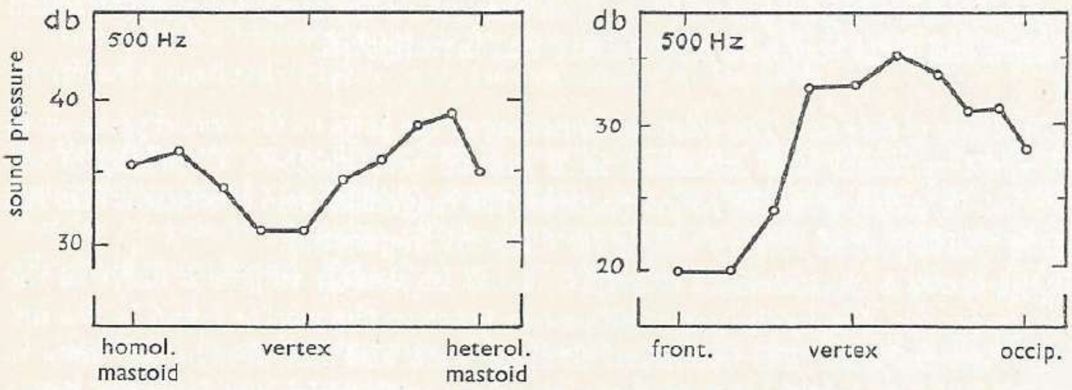

Fig. 27

Sound pressure as a function of the place on the skull where the bone conduction stimulus is given.

Fig. 27 shows the sound pressure in the auditory canal as a function of the place of the bone conduction oscillator on the skull under constant pressure for a frequency of 500 Hz. The smallest sound pressure was measured for frontal and occipital application. The sound pressure was greatest when the bone conduction receiver was placed parietally on the opposite half of the skull and on the two mastoids. The greatest sound pressure was therefore found on application on the parts of the skull where the bone conduction threshold is lowest, and the smallest sound pressure was found on application at places where this threshold is highest. This can be explained from the fact that, for a frequency of 500 Hz, the skull vibrates as a whole, due to which the vibrations at the sites of the cochlea and the auditory canal are the same.

§ 3. The origin of the sound pressure

To find out how in bone conduction the sound pressure in the auditory canal arises the mechanisms by which the air in the auditory canal can be made to vibrate, should be considered. There are various possibilities: by the *tympanic membrane*, by the *wall of the auditory canal* (in which the *capitulum mandibulae* is situated), and by the *ambient air*. Each of these adjoining systems will get into a state of vibration during bone conduction and will impart this vibration to the air of the auditory canal. The resulting sound pressure will be determined by the strongest of these factors, which probably will not be the same for all frequencies.

All factors mentioned above should therefore be taken into consideration when studying the development of the sound pressure in the auditory canal.

§ 4. The effect of changes in the position of the lower jaw on the sound pressure in the auditory canal and on bone conduction sensitivity

If, by relative vibrations with respect to the auditory canal, the lower jaw has a share in the development of the sound pressure in the canal, this sound pressure has to be influenced by certain changes with respect to the jaw. To study the significance of the lower jaw, the effect of such changes on the magnitude of the sound pressure and bone conduction sensitivity was investigated.

1. *Clenching of the jaws.* The effect of clenching of the jaws on the sound pressure in the auditory canal was measured in 8 normal test subjects. Clenching of the jaws led to a change in the sound pressure, the magnitude and sometimes also the sign of which proved to vary widely for different frequencies.
Fig. 28 shows a characteristic example. It was impossible to give a curve of the average results, due to the great differences between the results found in the different test subjects. The individual findings were also not always the same in repeated measurements. For example, the force with which the jaws are closed proved to have a great influence on the magnitude of the effect for certain frequencies.

The results confirmed the significance of the capitulum mandibulae for bringing about the sound pressure in the auditory cananl. As said before, according to von Békésy and Franke et al. on closure of the jaws the sound pressure would decrease and the bone conduction sensitivity be reduced as a result of the decline of the relative movements.

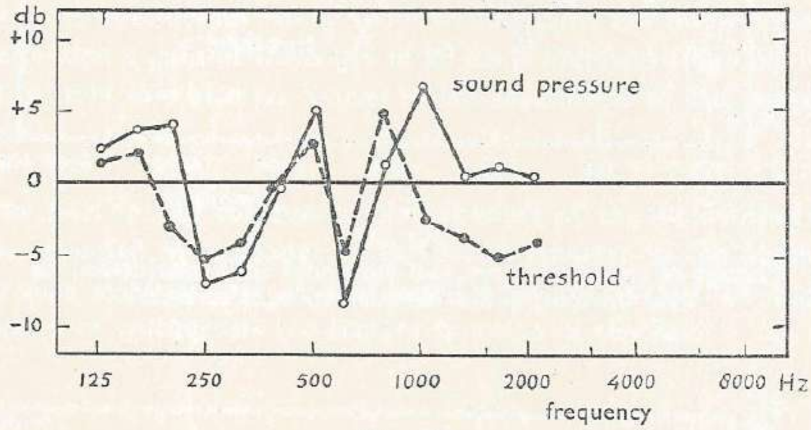

Fig. 28

Change of sound pressure and threshold shift for bone conduction on clenching of the jaws; example of a case.

We were however unable to confirm this, as clearly shown by Fig. 28. Widely varying effects were found for the various frequencies. The role played by the lower jaw, therefore does not seem to be as simple as assumed by those authors. In addition to the effect on the sound pressure, the effect on the bone conduction sensitivity exerted by clenching of the jaws was studied in the same test subjects.

Accurate determination of the threshold shift produced proved to be difficult as a result of its slight degree. It was however possible to confirm (also with great variations) that closure of the jaws has a markedly varying influence on bone conduction threshold for different frequencies.

As shown in the case of Fig. 28, the threshold shift did not correspond with the change of sound pressure and sometimes proved to be opposite to it.

It was further observed that for frequencies lower than 500 Hz the tone perceived acquired a markedly higher character on closing of the jaws.

3. *Opening of the jaws.* The effect of maximal opening of the mouth, by which a subluxation of the capitulum mandibulae can be obtained, was also studied. Similar irregularly changing effects on the sound pressure and bone conduction threshold were found. Fig. 29 shows an example.

4. *Unilateral lower jaw resection.* The sound pressures in left and right auditory canal were mutually compared in a patient with normal hearing in whom a unilateral lower jaw resection had been carried out. A markedly higher sound pressure was measured on the operated side, as shown by Fig. 30.

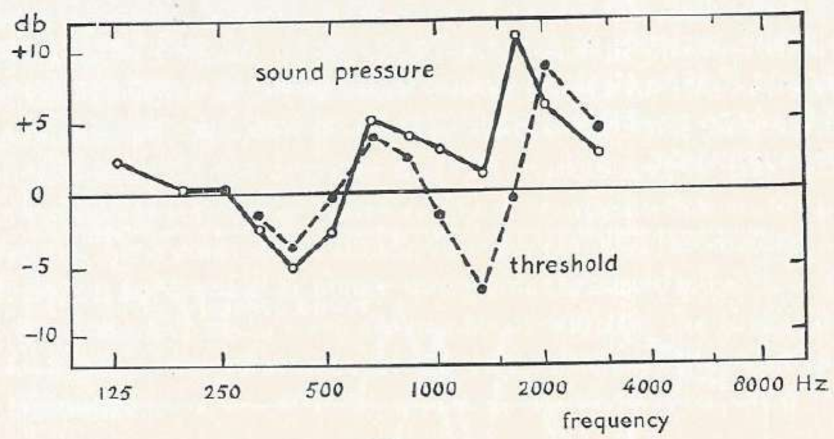

Fig. 29

Change of sound pressure and threshold shift conduction on wide opening of the mouth; example of a case.

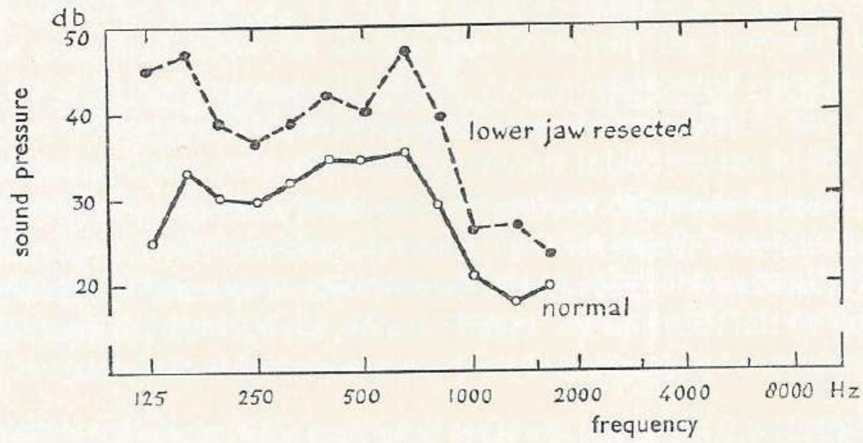

Fig. 30

Difference of sound pressure in the external auditory canals of a patient who had been subjected to a unilateral lower jaw resection.

This result also demonstrates the significance of the lower jaw in bringing about the sound pressure.

§ 5. The effect of experimental changes of the conduction apparatus on the sound pressure in the external auditory canal and on bone conduction sensitivity

If, as assumed by various investigators, the sound pressure in the auditory canal is produced by the vibrations of the eardrum, the expectation is justified that the sound pressure will be influenced by a change in the conduction apparatus. The effect on the sound pressure in the auditory canal following an increase of the stiffness or the mass of the conduction apparatus was therefore investigated in subjects with normal hearing. The measurements were carried out for 250, 500 and 1000 Hz.

A *stiffness increase* was established by producing a positive change of pressure of 50 cm water in the cavum tympani via the tuba by the method described on page 25.

As found in Chapter II, this pressure change causes a threshold loss for low frequencies of about 15 db for air conduction and of 5-10 db for bone conduction (Figs. 8 and 7).

This effect however did not cause a change in the magnitude of the sound pressure measured at the eardrum.

The *increase of mass* was effected by loading the eardrum with 500 mg water. This causes an air conduction loss of about 15 db for the low frequencies (Fig. 22); in bone conduction a gain of threshold of 20 db is obtained (Fig. 19).

However, in this case also no change in the magnitude of the sound pressure was recorded.

These results lead to the conclusion that changes of the conduction apparatus need not be attended by a change of the sound pressure in the auditory canal. This means that measurement of the sound pressure cannot be considered a reliable method of testing the conductive function of the ear.

§ 6. Conclusions

Although the results of the investigations described do not afford a quantitative understanding of the phenomena studied, they still lead to some important conclusions:

1. The experiments showed in various ways that a certain change of the sound pressure in the auditory canal need not be accompanied by a corresponding change in the bone conduction sensitivity. Conversely, it was shown that a change of the bone conduction threshold need not to be attended by a same change of sound pressure.

This conclusion is of importance in connection with the present bone conduction theory. This theory assumes that the sound pressure in the ear canal forms a factor in the establishment of the bone conduction perception by air conduction way. In view of our results, such a conception of the significance of the sound pressure in the auditory canal in bone conduction, is incorrect.

The results can be better understood by another approach to the problem. We therefore consider, in bone conduction, the different parts of the skull as a complex vibratory system (see Chapter VIII). Here the air of the auditory canal forms a system, the vibrations of which create a certain sound pressure. In the same way the cochlear fluid also forms a vibratory system; its vibrations determine the sound sensation. Both systems are coupled to each other via other vibratory systems, in particular the middle ear apparatus. A change in one of these systems results in a change of the two others. However there will be no simple relationship between the first change and the latter one (cf. Chapter I, § 4, § 5).

2. Various factors prove to be active in the production of the sound pressure. Their magnitude strongly depends on frequency. Quantitative analysis of each of these factors is difficult if not impossible.

It is however justified to assume that the vibrations of the bony part of the auditory canal play an important part. The lower jaw is also of significance. Sound energy from the outside is important for frequencies above 2000 Hz. Any significant role of the middle ear was not demonstrated.

3. Measurement of the sound pressure for clinic purposes does not seem to be of any value, because no fixed relationship was found between the sound pressure and the function of the conduction apparatus.

CHAPTER VI

BONE CONDUCTION THRESHOLD IN DISEASES OF THE MIDDLE EAR

As found in the foregoing chapters, experimental changes of the middle or external ear may exert a rather important influence on the sensitivity for bone conduction. This is not only of theoretical, but also of practical importance, as pathological changes of the middle ear, too, may be expected to affect the sensitivity for bone conduction. This implies that in affections of the middle ear the bone conduction threshold is no pure criterion for the perceptive function of the ear. In diseases of the middle ear the auditory acuity for bone conduction can not only be reduced by a perceptive loss but also by changes in the middle ear.

As changes produced experimentally in the middle ear were accompanied by threshold shifts of up to 20 db, it is likely that pathological changes also may exert such an influence on bone conduction.

In practice this has already been verified in otosclerosis, because, the Carhart notch found in this disease in the curve of the bone conduction threshold has proved to disappear in most cases after a fenestration operation.

A. THE VARIOUS FORMS OF BONE CONDUCTION THRESHOLD CURVES AND THEIR INCIDENCE

The results of hearing tests in 2000 patients of the Leyden University Clinic were studied. There were 1306 audiograms showing a difference between air conduction and bone conduction threshold curves. All audiograms were made by *continuous audiometry* (van Dishoeck, 1947), as in current use in the Leyden Clinic, with a Peekel audiometer type D4. The audiograms studied were made with the same audiometer by the same investigator.

1. Normal bone conduction curve

Entirely normal bone conduction curves were found in 213 cases. As is known, the sensitivity for bone conduction may remain normal while a treshold shift for air conduction of about 60 db may have occurred (Table II).

TABLE II

Classification of 213 audiograms with normal bone conduction, according to the average air conduction loss.

A.C. loss	10-< 20db	20-< 30db	30-< 40db	40-< 50db	50-< 60db	60-< 70db	Total
Number	21	55	67	42	22	6	213

2. Supranormal bone conduction curve

In 33 cases (39 audiograms) a bone conduction curve was found that locally exceeded normal threshold by more than 5 db. As shown by Table III, the cases concerned were for the most part children.

TABLE III

Classification into age groups of 33 patients with supranormal bone conduction threshold.

Age	5-< 10 yrs.	10-< 15 yrs.	15-< 20 yrs.	20 yrs. and older	Total
Number	14	8	7	4	33

Probably a physiologically lower bone conduction threshold at younger age is possible. Floux- Guyot believes that up to 15 years the bone conduction threshold for low frequencies is 5-15 db lower than normal. In our cases there was no manifest preference for particular frequencies (Table IV). Supranormal bone conduction sensitivity was found in the lower, middle as well as the higher parts of the tone scale.

TABLE IV

Distribution over the tone scale of supranormal bone conduction thresholds in 39 audiograms.

Frequency	250-500 Hz	500-1000 Hz	1000-2000 Hz	2000-4000 Hz	4000-8000 Hz
Number	21	18	30	17	4

To explain the lower bone conduction threshold in children, it is evident to seek a relationship with the not yet existing or only partially existing pneumatization of the mastoid.

3. Rising bone conduction curve

Audiograms with rising threshold curve were frequently found. In particular curves were found in which the loss was limited to frequencies lower than 1500 Hz. A typical example is given in Fig. 31.

226 of such audiograms with a loss of 10 db or more, were collected. The air conduction threshold curve was likewise of the rising type in a fairly large percentage of these cases, as shown by Table V.

TABLE V

Form of the air conduction audiogram in 226 cases with rising bone conduction threshold curve.

Rising curves				Other curves	Total
Steepness in db/octave	< 10	10-< 20	20-< 30		
Number	23	123	19		
	165			61	226

This justifies the supposition that here the bone conduction loss results from an *increase of stiffness* of the conduction apparatus. For in Chapter II we found on stiffness increase by means of pressure change a similar threshold loss for low tones with rising curve both for air and bone conduction.

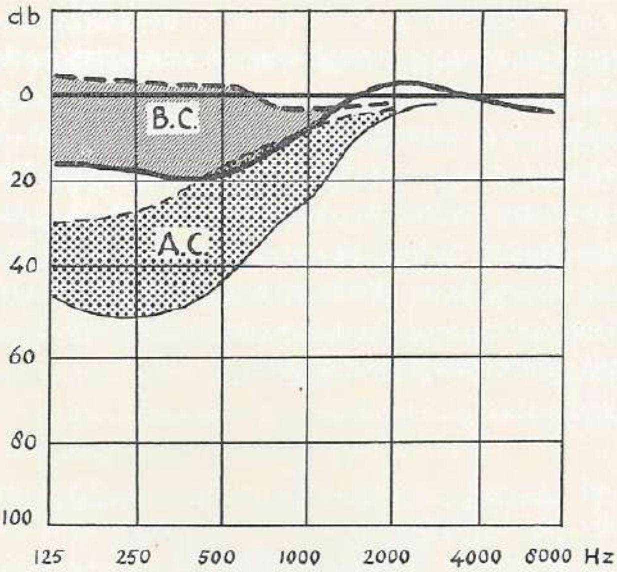

Fig. 31

Example of the rising type of bone and air conduction audiogram, in which a marked improvement occurred after treatment.

——— before treatment

– – – – – after treatment

That in conduction disturbances in general an increase of stiffness may occur, was also shown by our quantitative Gellé measurements, in which, as described before, usually smaller effects were obtained in cases with conduction impairment than is normally the case.

In a number of patients it was possible to confirm the supposition that these bone conduction losses are caused by a middle ear process because they could entirely or partially be abolished by treatment as in the case of Fig. 31. Such a bone conduction loss sometimes diminished after closing an existing eardrum perforation by means of a wad of cotton wool soaked in oil, by which the air conduction was improved.

4. Trough-shaped curve

A trough-shaped bone conduction loss was found in 140 of the audiograms analysed. This form of bone conduction threshold curve is known in otosclerosis, especially in the first stages. This is called the Carhart notch in the audiogram. In a great number of the trough-formed bone conduction audiograms found the patient indeed suffered from otosclerosis. In 33 cases, however, a chronic inflammatory process or its residues proved to exist as shown by Table VI.

TABLE VI

Aetiology of the middle ear disease in 152 cases with trough-shaped bone conduction loss.

Otosclerose	Otitis media etc.	Total
107	33	140

That inflammations may cause a trough-shaped bone conduction loss similar to that in otosclerosis, can be strikingly demonstrated by the case of a 35-year-old patient, who had suffered, for about 25 years, from recurrent otitis media on the left, which had given rise to a central eardrum perforation. His audiogram (Fig. 32) showed an air conduction loss of on an average 65 db with a trough-shaped bone conduction loss similar to that in otosclerosis. Closing off of the perforation with a wad of cotton wool with oil produced a gain of 20 db for air conduction and caused a partial disappearance of the bone conduction loss. Tympanoplasty later gave the same result, even to a higher degree.

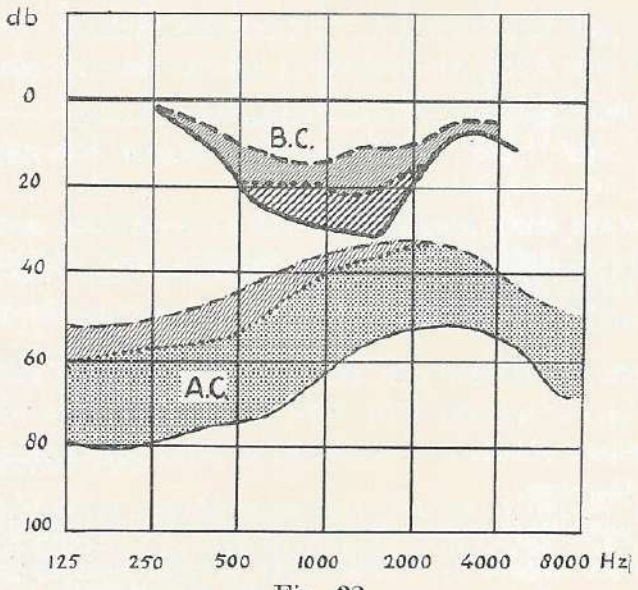

Fig. 32

Example of a trough-shaped bone conduction loss in chronic otitis media.
——— before treatment
· · · · · · · with sealing off of the existing perforation
– – – – – – post-operatively

5. Flat and declining curves

The largest group was formed by 688 audiograms with an almost flat or a declining bone conduction loss. These cases were not analysed in more detail. Probably various factors play a role in these losses. Undoubtedly, a so-called 'secondary inner ear damage' is usually the (most important) cause. It is however certain that also in cases with great bone conduction losses a considerable middle ear component can be present. It is not only the various experiments that lead to this conclusion. In these cases with 'combined types of deafness' we also sometimes observed a remarkable bone conduction gain after *tubal catheterization, tentative sealing off of an eardrum perforation*, or *operation*. Figs. 34, 35 and 36 give an example of each of these cases.

B. BONE CONDUCTION AUDIOGRAM IN VARIOUS MIDDLE EAR AFFECTIONS

1. Acute otitis media

The bone conduction threshold in acute otitis media has been studied by various investigators, by whom different results were obtained. Hulka (1941) described a gain for the low and a loss for the high tones. He explained the first by an impediment of the 'Schallabfluss' in the sense of Mach's ideas, the second by a toxic damage of the inner ear. Johansen (1948) found a loss for high frequencies alone; he attributed it to an increase of mass, to which he also ascribed the loss of air conduction which, according to him, was likewise strongest in the discant zone. Palva and Ojala (1953) usually did not find a shift of the bone conduction threshold, apart from in a few cases, where a loss of high tones existed.

These determinations of bone conduction sensitivity in otitis media therefore did not yield a clear result. This may partially be due to the fact that it is difficult to speak of a fixed abnormality in otitis media.

A forecast, on theoretical grounds, of the effect that may be expected on bone conduction, seems therefore dubious. It may be that, on the one hand, a gain occurs for low frequencies in analogy with the effect of eardrum loading, but on the other hand, the resistance may be increased due to the fluid and the swelling of the mucosa resulting in a threshold loss. It is further possible that loading of the windows plays a role.

2. Acute tubotympanitis (hydrotympanum)

Just as in otitis media, the abnormalities are often of a varying nature in acute tubotympanitis. The most important factor for the hearing function is probably the accumulation of fluid in the tympanic cavity (hydrotympanum). As a result of this, it is conceivable that loading (increase of mass) and greater resistance exert an effect. At the same time, an impediment of the function of the round window by the fluid seems possible.

We observed a number of cases of tubotympanitis with hydrotympanum, in which a bone conduction loss existed that proved to be the result of these middle ear affections, as after puncture and tubal catheterization a recovery of the threshold loss for bone conduction occurred, in addition to improvement of air conduction.

Löwy (1938) also described some cases of 'middle ear catarrh' with a gain in bone conduction after puncture.

Fig. 33 gives as an example one of our cases. It concerned a patient with complaints of unilateral deafness since a short time. His audiogram showed an air conduction loss of 40 db and a bone conduction loss of 20 db. Air conduction as well as bone conduction threshold were entirely normal after repeated puncture and tubal catheterization.

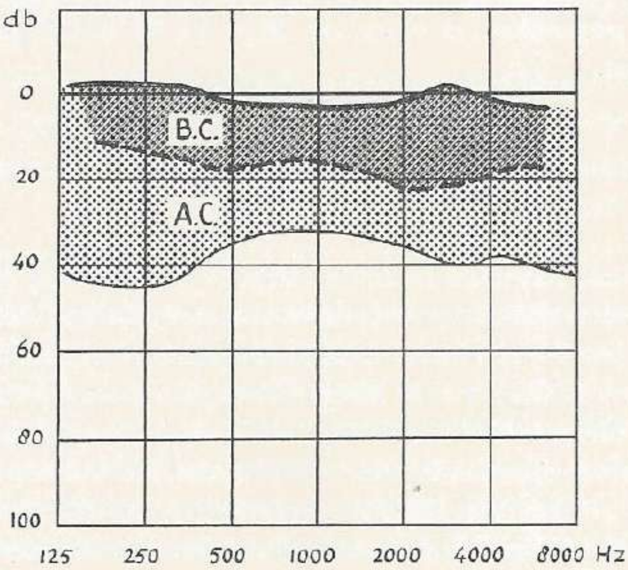

Fig. 33

Bone conduction loss in a patient with acute tubotympanitis with hydrotympanum.
====== before treatment
——— after treatment

3. Chronic otitis media and tubotympanitis

A greater or lesser threshold loss for bone conduction is found in the majority of patients with chronic infections middle ear processes. In general such bone conduction losses are regarded as a manifestation of a secondary cochlear damage.

As already remarked, it is however possible that this loss of bone conduction sensitivity is partially caused by the middle ear changes.

Retjö (1913) and later Krainz (1927) called already attention to the fact that this may occur in the case of a functional disturbance of the windows, in particular of the round window. Round about 1930 great attention has been paid to processes which might hinder the membrane of the round window in its vibrations, and efforts have been made to abolish these impediments by operation (Hughson et al.).

Apart from functional impairment of the windows, changes of stiffness, resistance and mass of the eardrum and the auditory ossicles, as seen in the experimental studies, may also influence bone conduction.

Such changes will always take place to a greater or lesser degree in chronic otitis media, chronic tubotympanitis, etc.

That they may indeed give rise to loss of bone conduction, is very clearly manifested by a few cases in which this loss proved to be partially reversible. Examples of this are given in Figs. 34, 35 and 36.

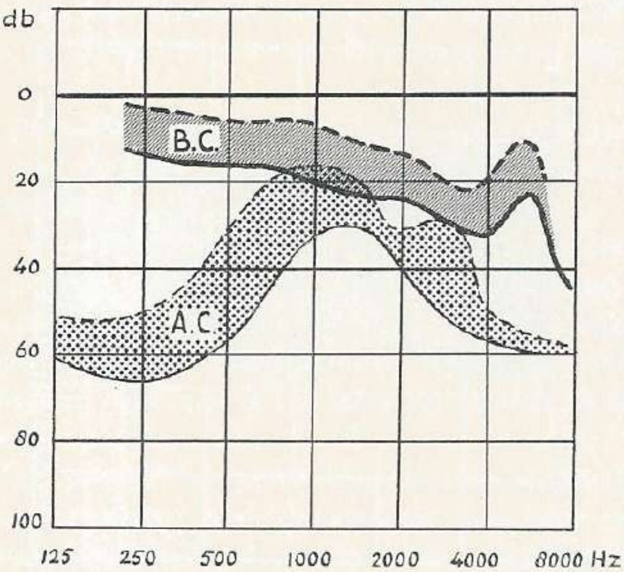

Fig. 34

Example of bone conduction improvement after treatment of the tuba Eustachii.

Fig. 34 shows the improvement of bone conduction in a patient after treatment with tubal catheterization. We found nine of such cases with a gain of bone conduction threshold demonstrated audiometrically, after Politzer treatment or tubal catheterization. Siebenmann (1892) and Aberg (1959) have also described some patients in whom this was observed.

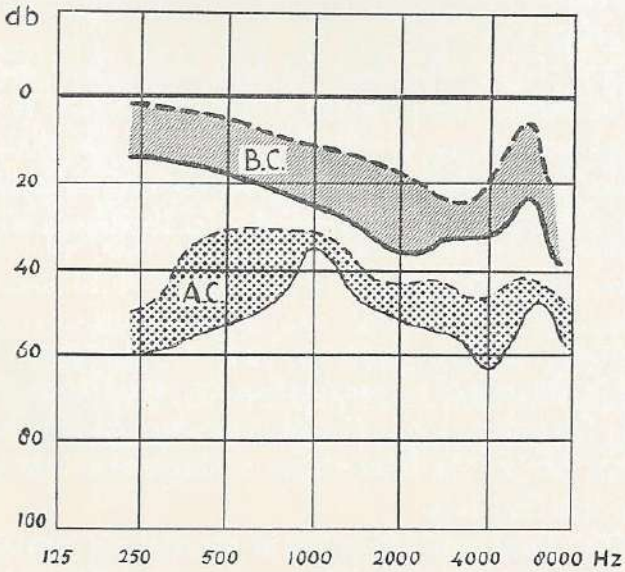

Fig. 35

Example of a case with bone conduction improvement following closing off an existing perforation of the eardrum by means of cotton wool soaked with oil.

Fig. 35 demonstrates a case in which an improvement in bone conduction was obtained after sealing off of an eardrum perforation with a piece of cotton wool soaked with oil. Similar effects on bone conduction were observed in nine other patients, but usually not so great.

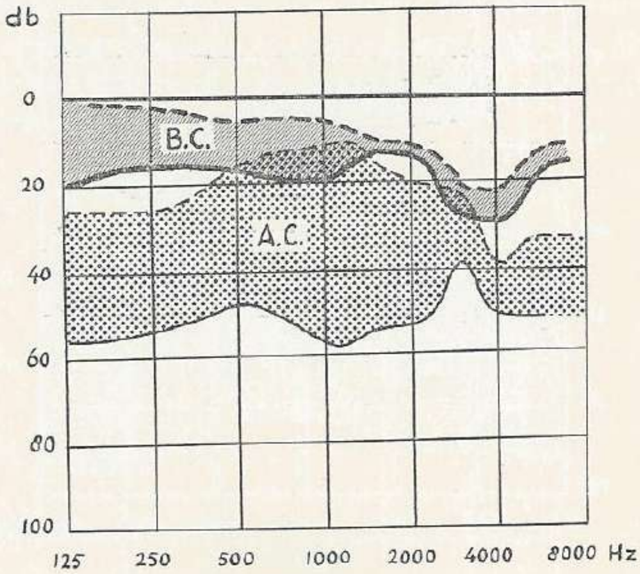

Fig. 36

Example of bone conduction improvement after tympanoplasty.

Fig. 36 finally, gives an example of a threshold gain for bone conduction after tympanoplasty.

The gain in these cases of bone conduction improvement by tubal catheterization, eardrum prothesis and operation occurred almost always for the same frequencies at which also a gain in air conduction was reached. No manifest predominance of a certain frequency range was found.

The examples given clearly show how the bone conduction loss in chronic otitis, etc., may partially be based on the affection of the middle ear. It may well be that this is more often and perhaps also to a higher degree the case than could be demonstrated in these cases. In chronic middle ear processes it is therefore not allowed to regard the bone conduction loss as a pure criterion for the degree of loss of perception.

4. Otosclerosis

At present, the existence of a bone conduction loss around 2000 Hz is fairly generally accepted in the case of stapes fixation by otosclerosis in its initial stages.

This is called the Carhart notch in the bone conduction threshold curve. Due to damage to the inner ear, in the later stages a progressive loss for all frequencies would be added to this first loss.

The existence of this bone conduction loss in otosclerosis was first clearly noticed in the study of audiograms of patients before and after labyrinthine fenestration. Various investigators found that, due to this operation, apart from the improvement in air conduction, some gain in bone conduction was obtained in the middle frequencies (Woods 1948, 1950, Juers 1948, Jongkees 1949, Shambaugh 1949, Woodman 1949, Carhart 1950). Carhart (1951) and McConnel and Carhart (1952) performed accurate determinations of this gain in bone conduction. According to Carhart, when making a prognosis of the operative results this bone conduction improvement can be taken into account. The majority of investigators seems to agree with this.

Rosen and Bergman (1959), however, did not find any improvement in bone conduction when analysing the results of 155 stapes mobilizations. It is not clear how this can be reconciled with the other results.

An *explanation of the Carhart notch* is impossible with the present bone conduction theory, as especially emphasized by Fournier. The thoughts often go in the direction of a failure of the 'contribution of air conduction to bone conduction', as a result of the stapes ankylosis. Carhart himself says that 'fixation of the stapes modifies the mechanical constants of the inner ear so that its frequency response to skull-bone vibrations is changed'.

In Chapter VIII we pleaded for approaching the bone conduction mechanism via principles obtaining for coupled vibratory systems, as in bone conduction all parts coupled to the bony skull will get in vibration together with it. The vibration of the ossicular-cochlear system (which can practically be regarded as an entity in bone conduction) is here essential for the sensation.

On fixation of the stapes foot plate, ossicular chain and cochlear fluid no longer form an entity, so that the influence of the ossicular chain on the cochlear fluid, will practically be eliminated. The vibration of the cochlear fluid probably undergoes the greatest influence at frequencies for which the vibratory amplitude of the auditory ossicles is greatest (or its impedance smallest), i.e., in its resonance area. In the case of otosclerosis, a shift of the bone conduction threshold at this place would therefore be understandable. Study of the various determinations of the resonance frequency of the conduction apparatus present in the literature yields as average result about 1100 Hz (Frank and Broemser: 1200 Hz, H.Kobrak: 550-800 Hz, von Békésy: 800-1500 Hz, Geffcken: 1800 Hz, Perlman: 750 Hz, Wever and Lawrence: 1000 Hz and Kirikae: 1000 Hz).

This is therefore lower than the frequency of 2000 Hz, for which, according to McConnel and Carhart and others, the bone conduction loss is maximal in otosclerosis. However, the measurements of McConnel and Carhart in the middle areas were only made at 1000, 1500 and 2000 Hz. Thus the deepest point of the Carhart notch might be situated somewhat lower than is generally assumed.

It is therefore not improbable that the trough-shaped bone conduction loss in stapes fixation occurs because the reinforcement, which the cochlear fluid normally undergoes by the vibrations of the auditory ossicles, remains absent.

CHAPTER VII

THEORY OF BONE CONDUCTION I

DEVELOPMENT AND PRESENT STATE

I. DEVELOPMENT

To understand the theoretical problems of the mechanism of hearing by bone conduction, study of the former theories and investigations in this field is of the greatest importance. Before the present state of the bone conduction theory is discussed, the most important phases to be distinguished in its development are therefore briefly dealt with.

Mach (1863). The 'Schallabfluss' theory, published by Ernst Mach in 1863 and subsequent years, is to be regarded as the first important theory on bone conduction. If—says Mach—sound energy can easily reach the labyrinth from the external world, it must, conversely, be possible that sound energy flows outward from the inner ear. If the skull, and with the skull the labyrinth, is set in vibration, a constant quantity of sound energy would be present at every place of this system; the magnitude of this quantity is determined by the local difference between energy 'Zufluss' and energy 'Abfluss'. A disturbance in one of these two factors would cause a change of the bone conduction perception.

The gain in bone conduction caused by occlusion of the auditory canal (Chapter I) was explained by Mach according to this theory by impediment of 'Schallabfluss'. The gain in bone conduction in conductive deafness that was formerly assumed on the strength of the prolonged Schwabach, would also be caused in this way.

In spite of criticisms, the theory of Mach gained great popularity for a long time. Even at present—in spite of the fact that, physically speaking, his theory is obsolete —it repeatedly is a subject of discussion. There is even a renewed interest as a result of investigations by Kley (see Chapter V).

Lucae (1864). Investigations of Lucae formed the beginning of a development in a quite different direction. Lucae noticed that the ossicular chain also vibrates in bone conduction. This led him, as the first, to the important conclusion that the conduction apparatus is of importance for bringing about the bone conduction perception.

Politzer (1864) believed that the acoustic nerve is directly stimulated in bone conduction, and that, in addition, the cochlea is stimulated via the air conduction route, because sound energy is transmitted to the eardrum and auditory ossicles from the temporal bone via the ligaments, etc.

Bezold (1885 and following years). According to Bezold, the basilar membrane can only be stimulated by vibrations of the auditory ossicles. He denied the existence of the 'osseal' bone conduction route as indicated by Mach and believed that there would only be a stimulation via the conduction apparatus, along the so-called 'osteotympanic' route. This explanation proved however difficult to put into harmony with the well-known clinical facts, in particular the preservation of bone conduction in otosclerosis and after a radical operation; this theory therefore received little support.

Brünings (1910) thought that there is both an osseal and an osteotympanic bone conduction route, and that the stimuli travelling via both routes interfere with each other in the inner ear. An increase of the phase difference would result in a loss of bone conduction sensitivity, and an increase of the difference in amplitude in a bone conduction gain.

Runge (1923) argued that the osteotympanic route predominates in low frequencies, and the osseal route in high frequencies.

Herzog (1926, 1930). The work of Herzog and Krainz is a contribution to the bone conduction theory that has received too little attention in the literature. Their publications laid the foundation for the theory adhered to at present.

According to Herzog, vibration of the skull causes an alternating compression and dilatation of the labyrinth. The incompressible cochlear fluid will have to yield under the influence of these opposite movements. The only places where this is possible are the two windows. Bezold, Politzer, and others, proved —according to Herzog—that the round window is about five times as elastic as the oval window; thus the outward and inward movement of the fluid will mainly take place at the fenestra rotunda. This means that a displacement of fluid arises from the scala vestibuli to the scala tympani, and vice versa; thus the basilar membrane vibrates in the same way as in air conduction.

At the same time however, the auditory ossicles are set into vibration; the stapes therefore also gives off impulses to the labyrinthine fluid. Due to the inertia of the ossicular chain, its oscillations will lag in phase with respect to the skull vibrations.

Herzog concluded that both mechanisms mentioned are active in bone conduction, and that they are in a state of competition as a result of this difference in phase.

Krainz (1926, 1930) tried to analyse the relationship between these factors, assumed to exist by Herzog. He found that occlusion of the auditory canal, rise of pressure in the meatus and filling of the auditory canal with water or mercury, caused a change in the amplitude and phase of the vibrations of the auditory ossicles with respect to those of the temporal bone. Krainz concluded from his results that a bone conduction gain arises if the vibratory amplitude of the ossicular chain is increased (occlusion, loading of the eardrum with mercury or water).

A gain would likewise occur if the phase difference between the vibrations of the ossicles and the temporal bone becomes smaller. According to Krainz this is the case on air pressure rise. (In Chapter II however we found a threshold loss on pressure change). Conversely, bone conduction would be reduced when a smaller difference in amplitude or a greater difference in phase occurs.

von Békésy (1932). An important contribution to the fundamental mechanism of bone conduction was rendered by von Békésy.

1. This author found that a sound sensation evoked via bone conduction, can be extinguished by an air conduction stimulus of the same frequency with a certain amplitude and phase. This fact proves that sound perception in bone conduction is based on the same cochlear process as in air conduction.

2. von Békésy further investigated for various frequencies the mode of vibration of the skull in bone conduction. He found that for 200 and 800 Hz the skull oscillates as a whole, and that for higher frequencies of 1100 and 1600 Hz the skull is subject to deformations by which it becomes divided into a number of vibrating segments.

3. Because he found the same effect of pressure change on bone as well as on air conduction von Békésy concluded that bone conduction perception during occlusion of the meatus is brought about by the sound pressure that arises in the auditory canal. He placed special emphasis on the relative movements of the capitulum mandibulae with respect to the meatal wall as cause of the development of this sound pressure (see also Chapter V).

4. With *open* meatus this sound pressure would not be of significance, and, according to von Békésy, bone conduction is then brought about by the relative vibrations of the auditory ossicles and by the compression of the cochlea.

Von Békésy elaborated Herzog's ideas in his conception of bone conduction stimulation by cochlear compression. Apart from the difference in elasticity of the windows, he especially mentioned the development of a fluid displacement from the semicircular canals to the scala vestibuli as cause of the fluid movements in the cochlea.

Guild (1936) discussed the different 'pathways' of sound transmission that are thought important in bringing about a stimulation of the cochlea in bone conduction. Based on his findings he considered the 'osseous pathway' as the most essential one.

E. Bárány (1938). Bárány dedicated an extensive monograph to the subject of bone conduction, in which he described a great number of personal investigations. Bárány also distinguished two modes of bone conduction stimulation:

1. The relative vibrations of the auditory ossicles and the cochlear fluid with respect to the skull, called by Bárány: 'inertia bone conduction' and considered by him the most important factor in the low frequencies.

2. The compression of the cochlea, the 'compression bone conduction', which predominates in the higher frequencies.

Bárány studied especially the 'inertia bone conduction' in his experiments.

In the first place he confirmed the existence of a translatory vibration of the skull as a whole for a frequency of 435 Hz. In addition he investigated by means of 'cancellation experiments' (von Békésy), the amplitude and phase of the cochlear vibrations on application of a bone conduction stimulus at various points of the skull. The amplitude proved minimal on application medially on the skull and maximal for stimulation at the sides of the head. On placement of the bone conduction receiver at one side the relative phase was opposite to that during application at the other side.

Bárány concluded from these results that stimulation of the cochlea in bone conduction is to be attributed to inertia movements of the ossicular chain. The magnitude of this inertia bone conduction depends *primarily* on the magnitude of the skull movements perpendicular to the vertical plane through the axis of the ossicular chain ($F = k. \cos \alpha$), and *secondarily*, on the 'inertia moment' of the chain. This inertia moment would normally be small because the distance between the centre of gravity and the rotation axis of the chain is very short due to its remarkable structure. According to Bárány the ossicular chain has this peculiar shape in order to keep the sensitivity for bone conduction small in proportion to that for air conduction.

The present bone conduction theory is based on the above described investigations of Herzog, Krainz, von Békésy and Bárány. This theory is fairly generally accepted, in spite of the fact that objections have been raised on clinical grounds (Hirsh, Fournier) and various quite different bone conduction hypotheses have been evolved (Kraus, Langenbeck, Kietz) and investigations with other results are published.

Kraus (1950) developed a theory in which he acknowledged only 'osseal bone conduction'. He supposed that bone conduction is normally attenuated by the middle ear and amplified by the external ear.

His ideas regarding the various bone conduction phenomena are however not in harmony with the facts. For example, Kraus explained the effect of change of pressure as a result of a decrease of the 'bone conduction amplifying' influence of the external ear, because the wall of the auditory canal would be anaemized. However, as found in Chapter II, the same effect on bone conduction arises if the change of pressure is produced in the cavum tympani instead of in the auditory canal. Kraus's idea that in the case of conduction disturbances, in particular otosclerosis, an increase of bone conduction sensitivity occurs (which fact might be explained with his theory), is conflicting with the general findings in this respect.

Jahn (1953) arrived at the quite new conclusion that the cochlear fluid is not only set in vibration by the vibrations of the auditory ossicles, but also via the porus acusticus internus due to the movements of the brain and cerebrospinal fluid. *Schneider* (1959), on the other hand was unable to demonstrate in animal experiments a stimulation of the cochlea in this way.

Langenbeck (1954). A second deviating bone conduction hypothesis was published by Langenbeck. This author assumed the existence of two interfering cochlear stimulations. On the one hand, the vibrations of the brain contents would stimulate the cochlea via the porus acusticus internus (Jahn): the 'labyrinth sound'. On the other hand, the vibrations of the capitulum mandibulae would give rise to a stimulation by air conduction way: the 'air sound'. The two impulses would be of opposite phase, and the air sound, before reaching the cochlea, would undergo an extra time delay. Further, the action of the air sound would be about double that of the labyrinth sound.

With this hypothesis, Langenbeck tried to explain the well-known bone conduction phenomena, in particular the phenomenon of lateralization in conduction disturbances, which he ascribed to a difference in phase between the stimulation of the left and the right cochlea. It is evident that the starting points of this theory are rather hypothetical, and that they are not in agreement with the experimental results in various respects. Our results are for example conflicting with Langenbeck's supposition of the role of the 'air sound'.

Kietz (1955) opposed Herzog's opinion that in bone conduction fluid movements in the cochlea can only arise if a window gives way. According to this author, in bone conduction, rotatory movements of the cochlea cause a displacement of fluid without giving way of the windows.

Kirikae (1959) investigated widely varying aspects of bone conduction in a great number of experiments. He studied, for example, amplitude and phase of the skull vibrations, the bone conduction threshold at different points of the skull and the 'inertia vibrations' of the auditory ossicles. Furthermore he investigated the effect of loading of the eardrum and of plugging of the windows. From his measurements of the elasticity of the windows he arrived at the conclusion that the round window is not five times but about twenty times as elastic as the oval window.

II. PRESENT STATE

At present a rather great agreement exists as regards the bone conduction theory. Almost all textbooks[1] in which the mechanism of bone conduction hearing is discussed, give the same theory, with only small differences. Three different ways of bone conduction are distinguished:

1. *Inertia bone conduction*,
2. *Compression bone conduction*,
3. *Bone conduction by air* ('secondary pathways of bone conduction', 'sekundäre Luftschall', 'osteotympanic bone conduction').

[1] 1. Stevens' *Handbook of experimental Psychology* (1951), chapter by von Békésy and Rosenblith, p. 118; 2. Hirsh: *Measurement of Hearing* (1952), p. 242; 3. Wever and Lawrence: (1954), *Physiological Acoustics* p. 223; 4. Langenbeck: *Leitfaden der praktischen Audiometrie* (1956), p. 79; 5. Kobrak: *The Middle Ear* (1958), chapter by Fournier, p. 92.

1. *Inertia bone conduction*

The way in which bone conduction would be brought about for low frequencies (< 800 Hz, according to others < 1500 Hz) is generally called: 'inertia bone conduction'.

For these frequencies the skull vibrates as a whole (Fig. 37), due to which the cochlea moves to and fro with respect to the ossicular chain which, as a result of its inertia, lags in vibration. Thus the terms 'translation movements of the skull' and therefore also 'translation bone conduction' are used, although rotatory movements of the skull are also considered of importance by some authors (Hirsh). Usually only inertia vibrations of the auditory ossicles are taken into consideration. Wever and Lawrence also regarded the inertia movements of the cochlear fluid of importance, but these would only play a role in vertical vibrations of the skull.

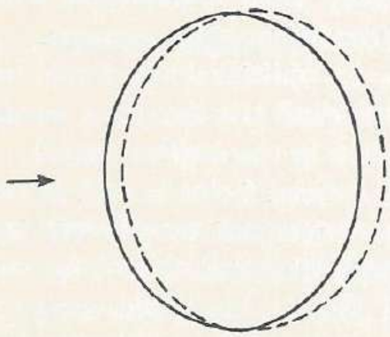

Fig. 37
Vibration of the skull as a whole, for frequencies up to 500 à 800 Hz.

2. *Compression bone conduction*

For higher frequencies, compression bone conduction would be of predominant significance. The deformations suffered by the skull for these frequencies (Fig. 38) would give rise to an alternating compression and expansion of the labyrinth. This results in a movement of fluid between the fenestra ovalis and fenestra rotunda, by which the basilar membrane is set in motion. Various causes are mentioned for the production of the fluid movement: the greater elasticity of the round window, which allows the greatest inward and outward movement of fluid at that site, the greater contents of the scala vestibuli and the displacement of fluid from the semicircular canals to the scala vestibuli (Fig. 39).

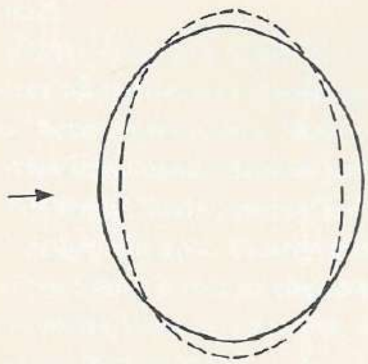

Fig. 38
Deformation of the skull for high frequencies as an example of which the vibrational pattern at 1100 Hz is given (after von Békésy).

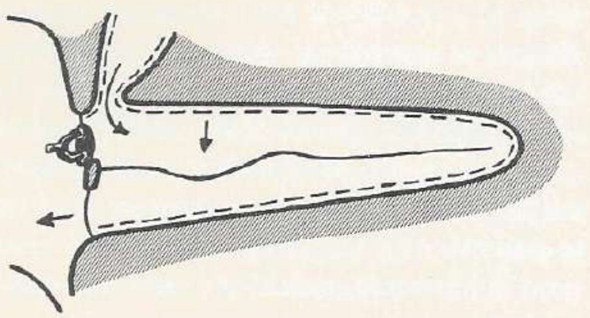

Fig. 39
Movement of the cochlear fluid by compression of the labyrinth (after Herzog, von Békésy).

3. *Bone conduction by air*

As third component of bone conduction a number of factors are mentioned, due to which the cochlea would be stimulated via the air conduction route.

a. The sound pressure, which arises in the auditory canal as a result of the relative movements of the capitulum mandibulae, is considered the most important of these factors. Some investigators regard this factor only of importance if the auditory canal is occluded, but others consider it also of significance under normal conditions with open ear.

b. An additional role would be played by the sound energy given off to the air by the skull and the bone conduction receiver, which contributes to the sound pressure in the auditory canal.

c. A third factor is said to be the sound energy given off by the walls of the cavum tympani to the air in the cavum, which acts on the eardrum in an opposite direction.

d. Finally, the sound energy transmitted to the conduction apparatus via the ligaments and the annulus tympanicus, would also be of importance.

CHAPTER VIII

THEORY OF BONE CONDUCTION II

—INADEQUACY OF THE PRESENT THEORY—

ANOTHER APPROACH TO THE MECHANISM OF BONE CONDUCTION

I. INADEQUACY OF THE PRESENT THEORY

Efforts to explain the clinical and experimental manifestations in bone conduction as found in our study, by means of the present bone conduction theory prove this theory inadequate in many respects.

This holds in the first place for the bone conduction threshold, as found in several affections of the middle ear. It is especially true as regards the bone conduction threshold in otosclerosis. For on the strength of this theory, it were to be expected (as also pointed out by Hirsh and by Fournier) that stapes fixation causes a reduction of the inertia bone conduction, which would result in a threshold loss for the low frequencies. Besides this, an augmentation of the compression bone conduction has to be expected, as the difference in elasticity of the windows has increased. This would result in a threshold gain for the high frequencies. Many investigators found however an almost normal bone conduction threshold in the initial stages of otosclerosis, for the low as well as for the high frequencies, while in the middle area around 2000 Hz a depression of 10-15 db, the 'Carhart notch', was found.

These facts are therefore by no means in harmony with the theory. In other forms of conductive deafness the theory is usually equally inadequate to explain the bone conduction threshold found in these cases. Here a decrease of the inertia bone conduction is just as well to be expected, while an augmentation of the compression bone conduction, too, is conceivable in certain cases. Never, however, is a threshold gain clearly present in the high frequencies. Several times (chapter VI) we found a loss in the bass zone, which indeed could be caused by a decrease of the inertia bone conduction. In other cases the bone conduction threshold is however entirely normal.

The results of our studies of the effect on bone conduction of occlusion, change of pressure, loading of the eardrum and their combinations are no more to be explained sufficiently with the present theory than the above-mentioned facts. From our experiments we concluded that all these effects are based on the production of a change in the middle ear apparatus. Thus, according to the theory, the expectation is warranted that a threshold shift is caused by an influence on the inertia bone conduction and that this therefore occurs for low frequencies. In fact, however, on occlusion and loading of the eardrum a threshold gain was observed up to 2500 Hz, while on pressure change a loss up to 4000 Hz, and a gain for 4000-8000 Hz was found. Apart from this frequency dependence of the effects, the theory can neither sufficiently explain these threshold shifts themselves.

The threshold gain following loading of the eardrum might be explained from an augmentation of the inertia bone conduction. The occlusion effect cannot be understood in this way however. In the present bone conduction theory, an increase of 'bone conduction by air conduction way' was therefore called in to help. The results of the experiments on the occlusion effect, as described in Chapter I, are however very difficult to reconcile with this conception. The loss in the low and middle frequencies by change of air pressure might be regarded as a diminution of the inertia bone conduction, even though the theory does not provide for effects up to 4000 Hz. It is however not allowed to regard a threshold gain in the region between 4000 and 8000 Hz as an increase of the compression bone conduction. Apart from the limited area in which this effect arises, this is also shown by the fact that the same phenomenon was observed in air conduction. Finally, it remains also unexplained why the loss is smaller in bone conduction than in air conduction.

In conclusion it must be said that the present bone conduction theory cannot sufficiently explain the various clinical and experimental bone conduction phenomena. In order still to understand these phenomena in the light of the theory, all sorts of suppositions might be made. The search for such solutions to arrive at a fitting theory involves the great danger that thus one gets farther from the truth.

So long as no more facts are known, it seems therefore better to refrain from evolving an alround bone conduction theory which, as it is, will have to be abandoned again within a few years.

II. ANOTHER APPROACH TO THE MECHANISM OF BONE CONDUCTION

As described in the previous chapter, the present bone conduction theory presupposes the existence of three different ways of bone conduction. It is usually assumed that these three types of bone conduction establish perception in mutual cooperation. As said before however, various bone conduction phenomena, clinical as well as experimental, cannot be understood sufficiently in this way.

We believe that it is better not to work with the principle of interfering 'modes' or 'pathways' of bone conduction It is more correct to regard the hearing organ as a mechanical vibratory system and to approach the mechanism of bone conduction hearing via the principles obtaining for vibratory systems.

As proved by von Békésy, bone conduction hearing is based on the same cochlear process as air conduction. In both cases the same vibration of the cochlear fluid and of the basilar membrane, arises, in spite of the fact that its establishment is entirely different.

In air conduction the cochlear fluid is set in vibration via the air and the middle ear apparatus. In bone conduction the whole skull is made to vibrate. In low frequencies ($<$ 800 Hz) a translation movement of the skull as a whole arises; for higher frequencies deformations occur and the skull is divided into vibrating segments by 'nodal lines'. Together with the bony skull, all parts of the head connected with it will also get into a certain vibratory movement. A whole complex of vibratory systems is thus set in motion as indicated in Fig. 40. Among these systems is the cochlear fluid, whose vibrations with respect to the bony cochlear capsule form the stimulus for the basilar membrane.

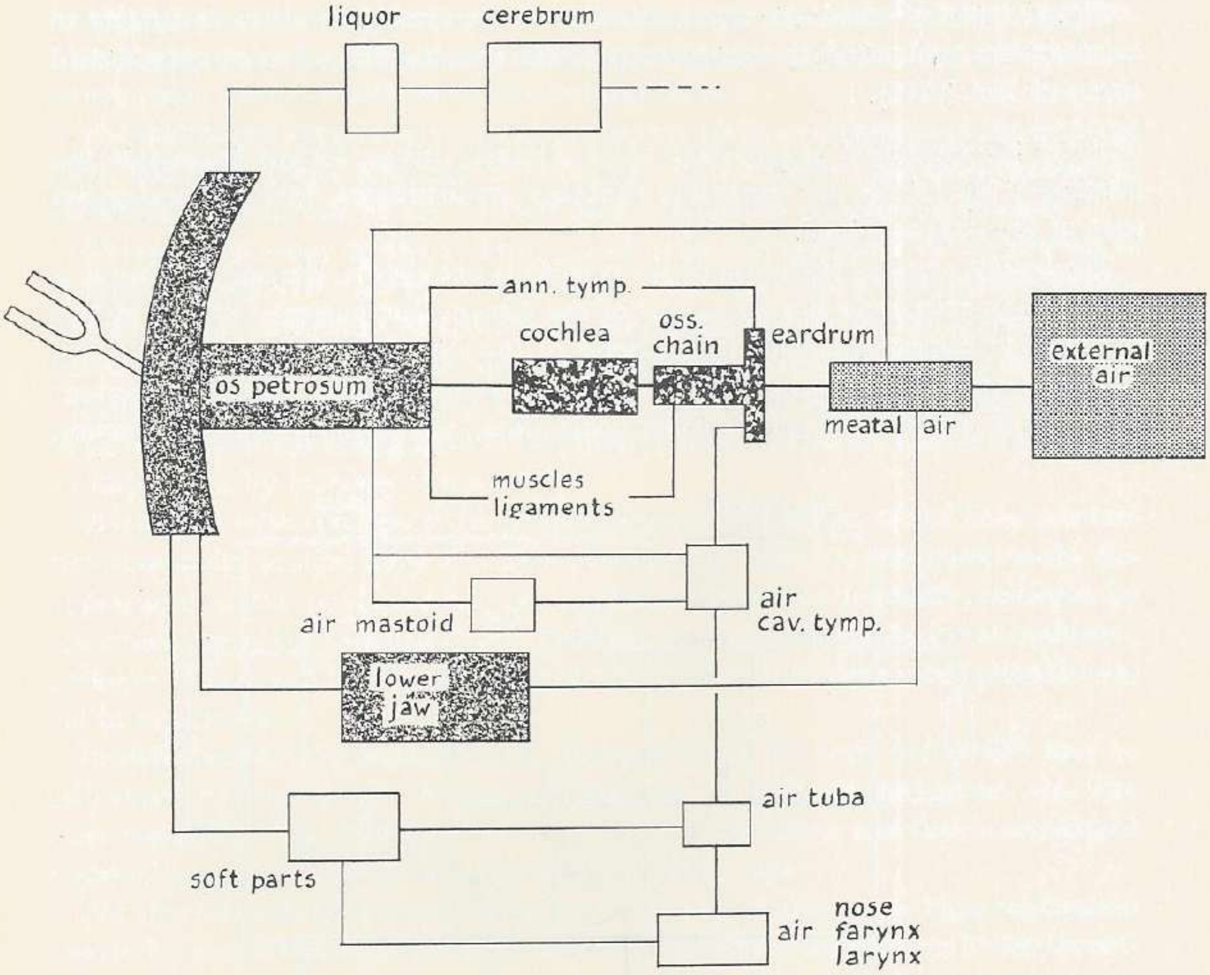

Fig. 40

The most important vibratory systems of the head with their mutual couplings.

Each of these systems is set in motion by adjoining systems, in which feedback effects play a role. The frequency of the forced vibration carried out by such a system is the same as that of the stimulus applied to the skull; its amplitude and its relative phase depend on mass, stiffness and resistance of the system and on the coupling with other systems. A change in one of these properties will, apart from an effect on the vibration of the system concerned, also exert an influence on the vibration of the other systems. An important variable factor is the place of application of the stimulus at the skull and its frequency, because this is decisive for the mode of vibration of the skull and the various parts of the head.

Such an intricate mechanical vibratory system can usually be more clearly illustrated with the help of an electric analogue. In an electric schema it is much easier to show how a change in a given circuit exerts an influence on other circuits.

As regards air conduction, various authors have designed an electric aequivalent of the hearing organ. For bone conduction this is more difficult, in view of the great number of unknown vibrating systems that take part in this case and because of the much more complicated driving mechanism.

Fig. 41 gives a schematic representation of the system as must be thought to exist in bone conduction. In various respects the schema is based on an unpublished study of Mol (1958).

The ear is represented as a system which is jointly driven; for low frequencies the driving of the middle ear apparatus probably predominates, for high frequencies that of the cochlear fluid.

The highly complex structure of the cochlea is not shown. For our purpose it is sufficient to substitute this by means of one circuit. The current *i* arising in this circuit then corresponds with the velocity of the stimulated hair cells.

Of the middle ear also only the essential elements have been represented: the mass of the eardrum and ossicular chain (Mm), the stiffness of the conduction

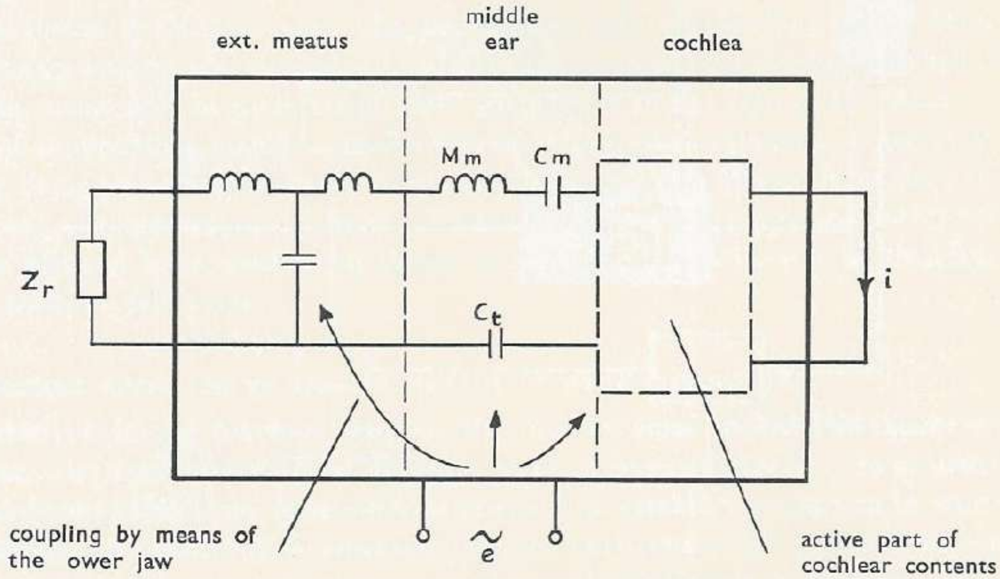

Fig. 41

Electric analogue of the ear in bone conduction.

e ~ bone conduction stimulus
i — current through the cochlear circuit ~ velocity of the stimulated hair cells

Mm ~ mass of the middle ear apparatus
Cm ~ stiffness of the middle ear apparatus
Ct ~ stiffness of the air of the tympanic cavity
Zr — radiation impedance of the concha

apparatus (Cm) formed by its ligaments and muscles and the stiffness (Ct) of the air of the tympanic cavity.

The external ear is depicted in the way a tube is generally represented, while in addition the radiation impedance (Zr) of the concha is included in the figure.

In bone conduction all these systems are set in vibration via the skull which has also a certain impedance. The lower jaw plays a special role in this complex as a result of his coupling on the one hand to the skull and on the other hand to the meatal air.

When the mechanism of bone conduction is approached in a way like this the various clinical and experimental bone conduction manifestations found may be explained as the consequence of a change in one of these vibratory systems. This change causes a shift of impedance relationships and coupling which has a repercussion on the vibration of the cochlear fluid.

The middle ear apparatus will exert in the first place an influence on the cochlear fluid, due to its direct coupling. That changes in it influence the bone conduction threshold is confirmed by the various bone conduction phenomena studied.

Change of pressure in the auditory canal or in the tympanic cavity proved to change the sensitivity for bone conduction. This effect has to be attributed to a change of the impedance of the middle ear apparatus due to the increase of its stiffness. Possibly a decrease of the force acting on the middle ear plays also a role.

Loading of the eardrum caused a threshold gain which effect is probably related to an increase of the acting force on the middle ear and possibly also to a change of its impedance by increase of mass.

Otosclerosis with fixation of the stapes causes a depression of the bone conduction sensitivity around 2000 Hz. This phenomenon might be attributed to the disappearance of the reinforcement the cochlear oscillations normally undergoe by the vibrations of the ossicular chain. This also appears from the fact that occlusion, pressure change and loading have less influence or none on bone conduction threshold in otosclerosis.

In *otitis media, tubotympanitis*, etc., the sensitivity for bone conduction may be influenced by middle ear changes like increase of stiffness, resistance, etc. The bone conduction loss that may be found in such affections and that is considered a loss of perception is sometimes partially based on this.

The air of the external auditory canal has an indirect influence on bone conduction sensitivity as a result of its coupling to the middle ear. This is shown by the threshold gain on occlusion of the auditory canal. Here, instead of the ambient air, an air column with a higher impedance is coupled to the middle ear. From a viewpoint of energy relationships this means that the meatal air takes up less energy which results in a threshold gain.

The lower jaw has proved to be another system of importance. Its influence takes place by means of its coupling between the skull and the meatal air. Change in this coupling proved to influence the sensitivity for bone conduction, probably partially due to a repercussion on the skull vibrations and partially via an effect on the air in the auditory canal.

As shown in Fig. 40, many other systems are also theoretically of importance: the contents of the skull, the air in the tympanic cavity and the mastoid, the nose and accessory sinuses, pharynx, larynx, etc. The real significance of these systems is however less great because in the practice changes in these systems do not exert a perceptible or clinically important influence.

APPENDIX

In our investigations some physical conceptions and formulas have been used. In this appendix a short survey of the principles of different forms of vibration will be given. As regards the general theory of vibration, the reader is referred to the textbooks dealing with this subject, e.g., Ph. Morse: *Vibration and Sound*.

1. *Simple harmonic vibration.* When a system with a mass m and a stiffness S is set into motion a simple harmonic vibration results, friction being neglected. Mathematic treatment shows that the period T of these undamped oscillations can be represented by the formula

$$T = 2\pi \sqrt{\frac{m}{S}}$$

Hence, the formula for the natural frequency f of the system is:

$$f = \frac{1}{2\pi} \sqrt{\frac{S}{m}}$$

2. *Damped oscillations.* When frictional forces are also taken into account the free oscillation frequency can be represented by the formula

$$f = \frac{1}{2\pi} \sqrt{\frac{S}{m} - \frac{Rm^2}{4\,m^2}}$$

in which Rm is the damping coefficient. The value of Rm depends on the amount of energy dissipated by the vibrating system. If the mass m is great and the dissipated energy relatively small (Rm small), the term $\frac{Rm^2}{4\,m^2}$ may be neglected, which means that the damping is small.

3. *Forced oscillations.* If, in contrast to the preceding case, a body is maintained in a state of vibration under the influence of a periodic external force, the vibrations are called forced oscillations.

The frequency of these forced vibrations is the same as the frequency of the applied or so called *driving* force.

The amplitude of vibration of the driven system will depend on the value of the acting force F and on the reaction of the system against this applied force which is called the mechanical impedance of the system. In formula this is:

$$a = \frac{F}{Z}$$

The mechanical impedance of a system consists of three factors: the mass reactance, the elastic reactance and frictional resistance of the vibrating body.

The *mass reactance Zm* is an inertia effect brought about by the mass *m* of the object, since mass opposes any change of motion. This factor increases directly proportional to the mass as well as to the frequency, its value being given by the formula

$$Zm = 2\pi f.m$$

The *elastic reactance Zs* is a result of the elasticity of a system or of its stiffness, which is opposing the vibratory displacement too. It is directly proportional to the value of *S* and inversely proportional to frequency so that

$$Zs = \frac{S}{2\pi f}$$

The *frictional resistance Rm,* which is the third limitation in evoking forced vibration, involves the dissipation of vibrational energy into heat. Its value does not vary with frequency; it only depends on friction.

Combining these limiting factors, we find for the total mechanical impedance *Z* the following formula

$$Z = \sqrt{Rm^2 + \left(2\pi f.\, m - \frac{S}{2\pi f}\right)^2}$$

as is shown in any textbook dealing with vibrational impedance problems. Hence it follows that *Z* reaches its minimum value when $2\pi f.m = \frac{S}{2\pi f}$ or when $f = \frac{1}{2\pi}\sqrt{\frac{S}{m}}$. The amplitude of vibration then reaches a maximum which represents the state of *resonance.*

According to the type of impedance factor which is predominant three different types of forced vibration have to be distinguished. The driven oscillator can mainly be stiffness-controlled, mass-controlled or resistance-controlled.

The oscillator is *stiffness-controlled* when the impedance is determined by the factor $\frac{S}{2\pi f}$. This will be the case if $\frac{S}{2\pi f}$ is greater than both $2\pi f.m$ and Rm or if

$$f < \frac{1}{2\pi}\sqrt{\frac{S}{m}}, \text{ or } f_{res.} \text{ and } < \frac{S}{2\pi Rm}$$

The oscillator is *mass-controlled* when the factor $2\pi f.m$ mainly determines the value of *Z* or if

$$f > f_{res.}, \text{ or } \frac{1}{2\pi}\sqrt{\frac{S}{m}} \text{ and } > \frac{Rm}{2\pi m}$$

The oscillator is *resistance-controlled* in the narrow range where

$$f < \frac{Rm}{2\pi m} \text{ and } f > \frac{S}{2\pi Rm}$$

SUMMARY

This thesis deals with a study of the effect exerted by various changes of the middle ear apparatus, the external ear and the lower jaw on the sensitivity of bone conduction. The clinical aspects of the phenomena investigated are discussed in detail. General conclusions are drawn based on the results obtained and another approach to the mechanism of bone conduction is described.

In Chapter I the *effect of occlusion of the auditory canal* is studied; after a historical survey, the author's personal experiments are discussed. The results are to be summarized as follows:

1. For bone conduction, occlusion of the auditory meatus proved to cause a threshold gain of 10-15 db for frequencies up to 1000 Hz; this gain declined for higher frequencies, no effect being present above 2000 Hz.

2. This occlusion effect persisted in a soundproof anechoic room with a residual noise below the masking threshold. Increase of the intensity level of the ambient noise to values higher than 35 db caused a proportionate increase of the occlusion effect.

3. As regards magnitude and sign, the occlusion effect proved to be dependent on the distance of the point of occlusion from the eardrum: occlusion of the extended auditory canal at $\frac{1}{2}\lambda$, λ, etc. caused a *maximal* threshold gain, and occlusion at $\frac{1}{4}\lambda$, $\frac{3}{4}\lambda$, etc. a *slight threshold loss*.

4. No fixed correlation proved to exist between the change of sound pressure at the eardrum by occlusion of the auditory meatus and the threshold gain produced.

These results lead to the conclusion that the *explanation of the occlusion effect* by means of the 'Schallabfluss' theory and the masking theory cannot be correct and that the theory of the increase of the air conduction factor of bone conduction, too, does not entirely agree with the results.

The conclusion is reached that the normal occlusion effect arises because on occlusion, instead of the ambient air, an air column with a higher impedance is coupled to the middle ear. From a viewpoint of energy relationships this means that the meatal air takes up less energy, which results in a threshold gain.

As regards the *clinical applications of the occlusion effect*, the usefulness of the occlusion test as a differential diagnostic means was confirmed. Next the 'faux-Bing' phenomenon (Fournier) was studied. Based on the results it is pointed out that this phenomenon can be explained as a normal localization process. Finally, emphasis is placed on the incorrectness of bone conduction audiometry with closed meatus (erroneously called: absolute bone conduction or C.O.A. in France), and on the errors through an occlusion effect due to a telephone receiver.

Chapter II deals with the *effect of a change of air pressure*. After a study of the literature, the author's personal experiments are described, which have led to the following results and conclusions:

1. Change of air pressure in the auditory canal or in the tympanic cavity (with elimination of an occlusion effect) caused a bone conduction threshold shift qualitatively the same as that in air conduction, viz.: a threshold loss below 4000 Hz, greatest for low frequencies and gradually decreasing above 1000 Hz, whereas a threshold gain arose between 4000 and 8000 Hz.

The conclusion was arrived at that these threshold shifts for bone and air conduction may be explained from a change of impedance of the middle ear apparatus as a result of an increase of its stiffness. The qualitative correspondence between the effect on bone conduction and on air conduction pleads in favour of the same state of vibration of the middle ear apparatus and the cochlear fluid in both cases.

2. The threshold shift for bone conduction was about two-thirds of that of air conduction. That the effect on bone conduction is less, might be attributed to a difference of impedance of the middle ear apparatus in bone conduction compared with that in air conduction. Another possibility would be that in the case of bone conduction the force acting on the middle ear apparatus decreases.

3. The effect of a positive pressure change in the auditory canal proved somewhat greater than that of a negative change, which was explained by regarding the middle ear apparatus as a system with asymmetric elasticity.

4. Finally, the clinical application of the effect, i.e., the *test of Gellé*, was studied. An effort was made to revise the theoretical background of this test. Subsequently a personal simple but accurate method for quantitative Gellé measurements is described, with some of the results obtained.

Chapter III describes the *effect of loading of the eardrum*. After a discussion of the former investigations the personal experiments are described, which led to the following results and conclusions:

1. Loading of the eardrum with water or mercury proved to cause a threshold gain for bone conduction of 20 db for frequencies up to 1000 Hz. This gain was less for higher frequencies, and no effect occurred above 2000 Hz.

This threshold gain reached its maximum of about 20 db for a loading mass of 300-500 mg and remained unchanged for greater loading.

The conclusion was reached that this bone conduction effect should probably be attributed to an increase of the force acting on the middle ear and possibly also to a change of its impedance by increase of mass.

2. A clear effect on the air conduction threshold was only measured if the loading mass covered the eardrum almost entirely. In this case a considerable loss was found for the high frequencies, which loss increased with the frequency. On greater loading a threshold loss also occurred for the low tones. This effect on air conduction can be explained from an increase of mass and resistance and possibly also of stiffness.

In Chapter IV the combined *effect of occlusion, change of pressure and loading* is studied. This led to the following findings:

1. During occlusion of the auditory canal the effect of a pressure change was greater than with open ear.
2. During loading, occlusion had no influence on bone conduction threshold.
3. The effect of a pressure change during loading was quite different from that in the normal ear: the curve of the threshold shift was displaced to the left.

An effort was made to give an explanation of these phenomena.

Chapter V deals with the *sound pressure in the auditory canal in bone conduction*. After a discussion and critical consideration of earlier publications, the author's personal investigations are described, which have led to the following results:

1. Below 1000 Hz the sound pressure was 10^{-4} times the stimulus, and decreased rapidly above this frequency. Its magnitude was further dependent on the point of application of the stimulus.
2. Various experiments proved that changes of the lower jaw exert an influence on the magnitude of the sound pressure and that these changes also cause a threshold shift for bone conduction. These two effects however differed as regards magnitude and sign.
3. Certain middle ear changes had no measurable effect on the sound pressure while they did influence the air and bone conduction threshold.

The following conclusions were drawn:

a. The lower jaw is a factor in the origin of the sound pressure in the auditory canal, but its role is not as simple as sometimes suggested.

b. Clinical determination of the sound pressure in the meatus to determine the function of the conduction apparatus, is no reliable method.

c. Changes of the sound pressure in the auditory canal need not be accompanied by corresponding changes of the bone conduction threshold, neither is this necessary in the reverse case. This is understandable if the mechanism in bone conduction is approached in the way described in Chapter VIII.

Chapter VI discusses the *bone conduction threshold in middle ear diseases*. In view of the fact that experimental changes of the middle ear may influence the bone conduction threshold, it is pointed out that this may also be expected in pathological changes. The results of a personal investigation into the incidence of various forms of bone conduction threshold curves are discussed:

1. In a number of cases, a bone conduction loss in the low frequencies was found, with rising curve. It is pointed out that this loss might be the result of increase of stiffness of the conduction apparatus. In a number of patients it was possible to confirm that this loss was partially based on a middle ear effect, because it diminished by treatment.
2. Bone conduction threshold curves with a depression for the middle frequencies (Carhart notch) are not only caused by otosclerosis but also by inflammatory processes. It has been found that such a depression can be abolished by treatment.

3. A supranormal bone conduction threshold was found in a number of audiograms mainly in children.

The bone conduction thresholds in otitis media, tubotympanitis, chronic inflammatory processes and otosclerosis are discussed. As regards otosclerosis it is known that the middle ear process causes a trough-shaped bone conduction loss (Carhart notch). An effort was made to explain this loss as a result of the disappearance of the reinforcement the cochlear oscillations normally undergoe by the vibration of the auditory ossicles.

In other affections of the middle ear also considerable bone conduction losses may arise due to the abnormality of the conduction apparatus. This is demonstrated in examples of patients in whom bone conduction improved considerably after treatment.

Chapter VII deals with the *development of the bone conduction theory*. Attention is paid to the work of Mach, Lucae, Politzer, Bezold, Brünings and Runge, following which the investigations of Herzog, Krainz, von Békésy and E. Bárány, which form the basis of the present theory, are discussed. Finally the more recent investigations and publications are dealt with, critical remarks being made on the new bone conduction theories of Kraus and of Langenbeck.

The *present generally accepted bone conduction theory*, as given in the textbooks, is discussed. The existence of three modes of bone conduction is assumed in this theory:

1. 'inertia bone conduction' (especially in the low frequencies),
2. 'compression bone conduction' (especially, in the high frequencies) and
3. 'bone conduction by air conduction way'.

These three modes of bone conduction, in mutual cooperation, would bring about the perception of sound.

Chapter VIII points to the *inadequacy of the present bone conduction theory*. It is shown that both the clinical bone conduction phenomena and the experimental manifestations as found in the preceding chapters, cannot sufficiently be explained with this theory.

Another approach to the mechanism of bone conduction is therefore suggested. Instead of working with 'interfering modes' or 'pathways of bone conduction', the bone conduction mechanism is approached according to the principles obtaining for a complex vibratory system. In bone conduction, all parts of the head are set in vibration, together with the bony skull, so that we can speak of a complex of coupled vibratory systems. The bone conduction phenomena, as found clinically and experimentally, should be regarded as the result of a change in the properties of these systems (i.e., middle ear, external ear, lower jaw, etc.). These changes cause alterations in the mutual relationships of the impedances and couplings, which has a repercussion on the vibration of the cochlear fluid.

RÉSUMÉ

La présente thèse est consacrée à l'étude des effets de diverses modifications de l'appareil de l'oreille moyenne, de l'oreille interne et de la mâchoire inférieure sur la sensibilité de la conduction osseuse. Les aspects cliniques des phénomènes étudiés sont ensuite examinés plus en détail. Des conclusions générales sont tirées à la lumière des résultats obtenus sur lesquels s'appuie la description d'une nouvelle méthode de travail en ce qui concerne le mécanisme de la conduction osseuse.

Le chapitre I étudie *l'effet de l'occlusion du canal auditif* au point de vue historique ainsi que sous la forme de recherches personnelles. Les résultats peuvent en être résumés comme suit:

1. il est apparu que l'occlusion de l'orifice du canal auditif entraîne, pour la conduction osseuse, un abaissement du seuil de 10 à 15 db pour les fréquences allant jusqu'à 1000 Hz; ce gain d'acuité auditive diminue d'amplitude pour les fréquences plus élevées et aucun effet n'a été observé pour les fréquences supérieures à 2000 Hz.
2. Cet effet de l'occlusion subsiste dans une chambre peu sonore avec un bruit résiduel inférieur au seuil d'assourdissement. L'augmentation du niveau d'intensité du bruit d'ambiance au delà de 35 db s'est accompagnée d'une augmentation proportionnelle de l'effet de l'occlusion.
3. L'effet de l'occlusion paraît être fonction, en importance et en signe, de la distance entre l'endroit de l'occlusion et la membrane du tympan: l'occlusion du canal auditif prolongé à $\frac{1}{2}\lambda$, λ etc. permet d'obtenir un *abaissement maximum* du seuil, tandis que l'occlusion à $\frac{1}{4}\lambda$, $\frac{3}{4}\lambda$ etc. et provoque une *légère augmentation* du seuil.
4. Il ne semble pas qu'il existe une relation fixe entre l'augmentation de la pression du son dans le cas d'une occlusion de l'orifice du canal auditif et l'abaissement du seuil qui en résulte.

Ces résultats permettent de conclure que *l'explication de l'effet de l'occlusion* par la théorie de 'l'écoulement du son' (Schallabflusztheorie) et par la théorie de l'assourdissement, ne peut pas être exacte, tandis que la théorie de l'augmentation du facteur de conduction aérienne de la conduction osseuse n'est pas non plus tout à fait en concordance avec les résultats.

On en conclut que l'effet de l'occlusion normal provient du fait que, dans le cas d'une occlusion au niveau de l'oreille moyenne, on utilise, au lieu de l'air extérieur, une colonne d'air à impédance plus élevée. Il en résulte que l'oreille externe absorbera moins d'énergie de telle sorte que l'on obtient ainsi un abaissement du seuil.

En ce qui concerne les *applications cliniques* de l'effet de l'occlusion, l'utilité de l'épreuve d'occlusion comme moyen de diagnostic différentiel lors de l'examen a été confirmée. Ensuite le phénomène du 'faux-Bing' (Fournier) a été étudié. Il

est signalé des résultats que ce phénomène s'explique comme étant un phénomène de localisation normal.Enfin, l'attention est attirée sur les inexactitudes de l'audiométrie par conduction osseuse en cas d'occlusion du conduit (appelée à tort conduction osseuse absolue ou C.O.A. en France) et sur les erreurs résultant d'un effet d'occlusion provoqué par le récepteur téléphonique.

Le chapitre II traite *l'effet de la modification de la pression atmosphérique*. Après avoir passé la litterature en revue, l'auteur décrit les expériences qu'il a fait personnellement et qui ont abouti aux résultats et conclusions suivants:

1. il est apparu que la modification de la pression atmosphérique dans le conduit auditif ou dans l'oreille moyenne entraîne, pour la conduction osseuse (après élimination de l'effet d'occlusion) un déplacement du seuil qui, du point de vue qualitatif, est équivalent à celui de la conduction aérienne, c'est-à-dire: une élévation du seuil pour les fréquences inférieures à 4000 Hz, la perte étant la plus importante pour les basses fréquences et diminuant progressivement pour les fréquences à partir de 1000 Hz, tandis que l'on enregistre un abaissement du seuil pour les fréquences situées entre 4000 et 8000 Hz.

On en conclut que ces déplacements du seuil pour la conduction osseuse et pour la conduction aérienne peuvent s'expliquer par une modification de l'impédance de l'appareil de l'oreille moyenne par suite d'une augmentation de sa rigidité. La correspondance qualitative entre l'effet sur la conduction osseuse et l'effet sur la conduction aérienne plaide en faveur de l'existence d'une même situation vibratoire de l'appareil de l'oreille moyenne et du liquide cochléaire dans les deux cas.

2. L'importance du déplacement du seuil pour la conduction osseuse représente environ les deux tiers de l'amplitude du déplacement du seuil pour la conduction aérienne. L'amplitude moins grande de l'effet sur la conduction osseuse pourrait être attribuée à une différence entre l'impédance de l'appareil de l'oreille moyenne dans la conduction osseuse et aérienne. Une autre possibilité pourrait être qu'il résulte une diminution de la force agissant sur l'appareil de l'oreille moyenne.

3. L'effet de l'augmentation de la pression dans le conduit auditif a été un peu plus fort que celui de la diminution de la pression; l'auteur explique ce phénomène en considérant l'appareil de l'oreille moyenne comme un système à élasticité asymétrique.

4. Enfin, l'application clinique de cet effet, à savoir *l'épreuve de Gellé*, a été étudiée. A cette occasion, l'auteur a tâché de revoir les fondements théoriques de cette épreuve. Il décrit ensuite une méthode simple et cependant précise qu'il a lui-même mise au point pour l'établissement de mesures quantitatives dans l'épreuve de Gellé et communique quelques résultats obtenus avec cette méthode.

Le chapitre III traite de *l'effet de la surcharge du tympan*. Après une revue de la littérature les expériments personnels sont décrits, lesquels ont abouti aux résultats et conclusions suivants:

1. La surcharge du tympan à l'aide d'eau ou de mercure entraîne, pour la conduction osseuse, un abaissement du seuil de 20 db pour les fréquences jusqu'a

1000 Hz. Pour les fréquences supérieures à 1000 Hz ce gain est moins important et l'on n'observe plus aucun effet au delà de 2000 Hz.

L'abaissement du seuil atteignit son maximum de 20 db avec une charge de 300 à 500 mg et n'accusa plus de changement pour les charges supérieures.

On en conclut que cet effet sur la conduction osseuse doit probablement être attribué à une augmentation de la force agissant sur l'oreille moyenne et possiblement à une modification de l'impédance par augmentation de la masse.

2. En ce qui concerne le seuil de la conduction aérienne, un effet nettement apparent n'a été mesuré que dans les cas où la masse de surcharge recouvrait pratiquement tout le tympan. Dans ce cas, on a enregistré une perte considérable pour les fréquences élevées, cette perte devenant plus importante à mesure que la fréquence augmentait. Avec une surcharge plus forte, on enregistra également une élévation du seuil pour les basses fréquences. Cet effet sur la conduction aérienne peut être expliqué par l'augmentation de la masse, de la résistance et, peut-être aussi, de la rigidité.

Le chapitre IV est consacré à une étude de *l'effet combiné de l'occlusion, de la modification de la pression et de la surcharge*. Les constatations qui ont été faites à cette occasion sont les suivantes:

1. L'effet de la modification de la pression pendant l'occlusion du conduit auditif était plus important que lorsque le conduit auditif est ouvert. 2. Dans les cas où l'on recourt à la surcharge, l'occlusion n'avait aucun effet sur le seuil de la conduction osseuse. 3. Pendant une surcharge, l'effet de la modification de la pression était tout différent de celui que l'on enregistre pour l'oreille normale: la courbe du déplacement du seuil a été déviée vers la gauche. L'auteur a essayé de donner une explication de ces résultats.

Le chapitre V est consacré à une étude de *la pression du son dans le conduit auditif en cas de conduction osseuse*. Après une discussion et un examen critique de diverses publications antérieures, l'auteur décrit ses propres recherches qui ont abouti aux résultats suivants:

1. Pour les fréquences inférieures à 1000 Hz, la pression du son représente une 10^4 fraction du stimulus et diminue rapidement pour les fréquences supérieures. L'importance de la pression du son dépend en outre de l'endroit ou l'excitation est appliquée.

2. Il a été constaté au cours de diverses expériences que des modifications apportées à la mâchoire inférieure ont une influence sur l'importance de cette pression du son et entraînent en outre un déplacement du seuil pour la conduction osseuse. Ces deux effets furent différents en importance et en signe.

3. Il est apparu que certaines modifications dans l'oreille moyenne n'avaient aucun effet mesurable tout en influençant le seuil de la conduction osseuse et aérienne.

Les conclusions que l'on a tirées de ces résultats sont les suivantes:

a. La mâchoire inférieure joue un rôle dans l'établissement de la pression du son dans le conduit auditif, mais ce rôle n'est pas aussi simple qu'on le représente parfois.

b. La détermination clinique de la mesure de la pression du son dans le conduit auditif pour en tirer des déductions concernant l'état fonctionnel de l'appareil de conduction n'est pas une méthode sûre.

c. Les modifications de la pression du son dans le conduit auditif ne vont pas nécessairement de pair avec des déplacements correspondants du seuil de la conduction osseuse et l'inverse est encore plus vrai. Ceci s'explique lorsque le problème du mécanisme en cas de conduction osseuse est abordé de la manière décrite dans le chapitre VIII.

Le chapitre VI traite du *seuil de la conduction osseuse en cas d'affections de l'oreille moyenne*. Partant du fait que des modifications expérimentales apportées à l'oreille moyenne peuvent influencer le seuil de la conduction osseuse, l'auteur fait remarquer que l'on peut s'attendre à ce que tel soit également le cas pour des modifications pathologiques. Les résultats de recherches personnelles de l'auteur au sujet de la fréquence de différentes formes de courbes du seuil de la conduction osseuse sont discutés:

1. Une perte de conduction osseuse pour les basses fréquences avec une courbe d'allure montante a été enregistrée dans un certain nombre de cas. L'auteur attire l'attention sur le fait que cette perte pourrait être la conséquence d'une augmentation de la rigidité de l'appareil de conduction. Chez quelques patients présentant une perte de ce genre, on a pu établir que celle-ci reposait sur un effet de l'oreille moyenne, étant donné qu'elle disparut sous l'action du traitement.

2. On a constaté que des courbes du seuil de la conduction osseuse avec une dépression pour les fréquences moyennes (Carhart-notch) peuvent se produire non seulement en cas d'otosclérose, mais également à la suite de processus inflammatoires. Il est apparu d'autre part que l'on pouvait faire disparaître une telle dépression par le traitement.

3. dans un certain nombre d'audiogrammes, on a trouvé un seuil de conduction osseuse supranormal, ce phénomène semblant surtout concerner les enfants.

L'auteur consacre une discussion au seuil de la conduction osseuse en cas d'otite moyenne, de tubo-tympanite, de processus inflammatoire chronique et d'otosclérose.

En ce qui concerne l'otosclérose, on sait que dans ce cas l'anomalie de l'oreille moyenne provoque une perte en cuvette de la conduction osseuse (Carhart-notch). L'auteur s'efforce d'expliquer cette perte comme une conséquence de l'absence du renforcement de la vibration du liquide cochléaire par la vibration des osselets de l'oreille.

On a cependant constaté que dans d'autres affections de l'oreille moyenne également, l'altération de l'appareil de conduction pouvait donner lieu à une perte importante de la conduction osseuse. Ceci est démontré par des exemples tirés des cas de patients chez lesquels la conduction osseuse s'était notablement améliorée sous l'action du traitement.

Le chapitre VII est avant tout consacré à une *revue de l'évolution de la théorie de la conduction osseuse*. L'auteur s'arrête aux travaux de Mach, de Lucae, de Politzer, de Bezold, de Brünings et de Runge. Viennent ensuite les recherches de Herzog, Krainz, von Békésy et E. Bárány qui ont jeté les bases de la théorie actuelle. Enfin, l'auteur examine les recherches et les publications plus récentes et fait la critique des nouvelles théories de Kraus et de Langenbeck sur la conduction osseuse.

Il traite ensuite de *la théorie de la conduction osseuse généralement admise á l'heure actuelle* et telle qu'elle est reproduite dans les traités qui lui ont été consacrés. On admet l'existence de trois modes de conduction osseuse: la conduction osseuse 'par inertie' (surtout pour les basses fréquences); la conduction osseuse 'par compression' (surtout pour les fréquences élevées); et la 'conduction osseuse par voie de conduction aérienne'. Ces trois formes de conduction osseuse donneraient naissance à la perception en agissant de concert.

Le chapitre VIII met l'accent sur *l'insuffisance de la théorie actuelle* de la conduction osseuse. Il apparaît que les phénomènes cliniques de la conduction osseuse aussi bien que les phénomènes expérimentaux décrits dans les chapitres précédents ne peuvent pas être expliqués de façon suffisante par cette théorie.

C'est pourquoi l'auteur propose une *nouvelle méthode pour aborder le problème du mécanisme de la conduction osseuse.* Au lieu de travailler avec des 'modes interférents' ou des 'voies interférentes' de la conduction osseuse, il aborde le problème du mécanisme de la conduction osseuse suivant les principes qui sont d'application pour un système de vibration complexe. Dans la conduction osseuse, avec le crâne osseux, toutes les parties de la tête sont en effet mises en vibration de telle sorte que l'on a affaire à un complexe de systèmes vibratoires couplés. Les phénomènes cliniques et expérimentaux que l'on a observés à propos de la conduction osseuse doivent être considérés comme le résultat d'une modification des propriétés de ces systèmes (en l'occurence, l'oreille moyenne, l'oreille externe, la mâchoire inférieure, etc.). Ces modifications entraînent des changements dans les rapports réciproques des impédances et des couplages, changements qui ont une répercussion sur la vibration du liquide cochléaire.

ZUSAMMENFASSUNG

In der vorliegenden Dissertation wird die Wirkung verschiedener Veränderungen am Mittelohrapparat, dem äusseren Ohr und Unterkiefer auf die Empfindlichkeit der Knochenleitung untersucht. Auf die klinischen Aspekte der untersuchten Erscheinungen wird näher eingegangen. Auf Grund der erhaltenen Resultate werden allgemeine Schlüsse gezogen und eine neue Betrachtungsweise des Knochenleitungsmechanismus beschrieben.

Im 1. Kapitel wird *der Effekt des Gehörgangsverschlusses* historisch und in der Form von eigenen Untersuchungen betrachtet. Die Resultate hiervon können wie folgt zusammengefasst werden:

1. Wie sich herausstellte, verursachte Verschluss der Gehörgangsöffnung einen Schwellengewinn von 10-15 db für Frequenzen bis 1000 Hz für die Knochenleitung; bei höheren Frequenzen nahm dieser Gewinn an Grösse ab, während bei über 2000 Hz überhaupt kein Effekt zu verzeichnen war.

2. In einer geräuscharmen Kammer mit einem Restlärm, der unter der Maskierungsschwelle lag, blieb dieser Okklusionseffekt erhalten. Bei der Vergrösserung des Intensitätsniveaus des Umgebungslärms über 35 db nahm der Okklusionseffekt in gleichem Masse an Grösse zu.

3. Der Okklusionseffekt erwies sich abhängig von der Entfernung des Verschlussortes vom Trommelfell: Sperrung des verlängerten Gehörgangs auf $\frac{1}{2}\lambda$, λ etc. verursachte einen *maximal grossen* Schwellengewinn, Sperrung auf $\frac{1}{4}\lambda$, $\frac{3}{4}\lambda$ etc. einen *geringen Schwellenverlust*.

4. Es stellte sich heraus, dass zwischen der Änderung der Schalldruckgrösse am Trommelfell durch Verschluss der Gehörgangsöffnung und dem dabei auftretenden Schwellengewin kein fester Zusammenhang besteht.

Diese Resultate führen zu dem Schluss, dass die *Erklärung des Okklusionseffektes* mittels der Schallabflusstheorie und Maskierungstheorie nicht richtig sein kann, während die Theorie von der Zunahme des Luftleitungsfaktors der Knochenleitung auch nicht ganz mit den Ergebnissen übereinstimmt. Es wird gefolgert, dass der normale Okklusionseffekt dadurch zustande kommt, dass beim Verschluss die Aussenluft durch eine Luftsäule von höherer Impedanz ersetzt wird. Hierdurch wird durch das äussere Ohr weniger Energie afugenommen, was zur Folge hat, dass ein Schwellengewinn auftritt.

Hinsichtlich der *klinischen Anwendungen des Okklusionseffektes* bestätigte die Untersuchung die Brauchbarkeit der Verschlussprobe als Differentialdiagnostikum. Weiter wurde das 'Faux-Bing-Phänomen' (Fournier) untersucht. Es wird darauf hingewiesen, dass dieses Phänomen als normale Lokalisationserscheinung zu erklären ist. Schliesslich wird auf die Ungenauigkeit der Knochenleitungsaudiometrie bei verschlossenem Meatus (zu Unrecht absolute Knochenleitung oder in Frankreich C.O.A. genannt) und auf Fehler durch einen Okklusionseffekt, der durch den Telephonhörer verursacht wurde, hingewiesen.

Das 2. Kapitel behandelt der *Effekt von Luftdruckänderung.* Nach einer Literaturbetrachtung werden die eigenen Experimente beschrieben, die zu folgenden Resultaten und Schlüssen geführt haben:

1. Luftdruckänderung im Gehörgang oder Mittelohr (bei Ausschaltung des Okklusionseffektes) verursachte eine Schwellenverschiebung, die quantitativ der der Luftleitung gleich war, nämlich: einen Schwellenverlust unter 4000 Hz, der am grössten bei den niedrigen Frequenzen war und oberhalb 1000 Hz allmählich abnahm, während zwischen 4000 und 8000 Hz ein Schwellengewinn entstand.

Hieraus folgerte man, dass derartige Schwellenverschiebungen für Knochen- und Luftleitung aus einer Impedanzveränderung des Mittelohrapparates als Folge seiner zunehmenden Versteifung erklärt werden können. Die qualitative Übereinstimmung zwischen dem Effekt der Knochenleitung und Luftleitung spricht für einen gleichen Schwingungszustand des Mittelohrapparates und der Kochlearflüssigkeit in beiden Fällen.

2. Die Schwellenverschiebung für Knochenleitung erwies sich im grossen als etwa 2/3 derjenigen für Luftleitung. Dass die Wirkung auf die Knochenleitung kleiner ist, könnte einer Differenz in Impedanz des Mittelohrapparates für Knochen- und Luftleitung zugeschrieben werden, oder möglich dem Entstehen einer Abnahme der auf den Mittelohrapparat wirkenden Kraft.

3. Der Effekt bei Druckerhöhung im Gehörgang erwies sich als etwas höher als der bei Drucksenkung, was sich erklären liess, indem man den Mittelohrapparat als ein System mit asymmetrischer Elastizität auffasste.

4. Schliesslich wurde die klinische Anwendung des Effektes, nämlich der *Gellé-scher Versuch,* einer Betrachtung unterzogen. Hierbei hat man versucht, den theoretischen Hintergrund der Probe zu revidieren. Dann wird eine eigene, einfache und doch genaue Methode für quantitative Gellé-Messungen beschrieben sowie einzelne dabei erhaltene Resultate.

Das 3. Kapitel handelt von der *Effekt der Trommelfellbelastung.*

Nach einer Betrachtung der Literatur werden die eigenen Experimenten beschrieben, die zu folgenden Resultaten und Schlüssen geführt haben:

1. Belastung des Trommelfells mit Wasser oder Quecksilber verursachte für die Knochenleitung einen Schwellengewinn von 20 db für Frequenzen bis 1000 Hz. Bei höheren Frequenzen war der Gewinn geringer, während oberhalb 2000 Hz keine Wirkung mehr auftrat.

Der Schwellengewinn erreichte sein Maximum von 20 db bei einer belastenden Masse von 300-500 mg und blieb darüber unverändert.

Hieraus wurde die Schlussfolgerung gezogen, dass dieser Knochenleitungseffekt vermutlich einer Zunahme der auf das Mittelohr wirkenden Kraft zugeschrieben werden muss und möglich auch einer Impedanzveränderung durch Zunahme der Masse.

2. Ein deutlicher Effekt auf die Luftleitungsschwelle war allein dann festzustellen, wenn die belastende Masse das Trommelfell praktisch bedeckte. In diesem Falle wurde ein beträchtlicher Verlust für die hohen Frequenzen gefunden, der zunahm, je höher die Frequenz war. Bei grösserer Belastung entstand auch eine Schwellensenkung für die niederen Töne. Diese Wirkung auf die Luftleitung kann durch Zunahme der Masse und des Widerstandes wie möglicherweise auch der Steife erklärt werden.

Im 4. Kapitel wird die kombinierte *Effekt von Okklusion, Druckänderung und Belastung* untersucht. Hierbei wurde gefunden:

1. dass der Effekt der Druckänderung während eines Gehörgangsverschlusses grösser war als bei offenem Ohr. 2. dass Verschluss während der Belastung keinen Einfluss auf die Knochenleitungsschwelle hatte. 3. dass der Effekt der Druckänderung während Belastung ganz anders ist als beim normalen Ohr: Die Kurve der Schwellenverschiebung war nach links gerückt. Es wurde versucht, eine Erklärung dieser Resultate zu geben.

Das 5. Kapitel behandelt den *Schalldruck im Gehörgang bei Knochenleitung*. Nach einer Besprechung und kritischen Betrachtung früherer Veröffentlichungen werden eigene Untersuchungen beschrieben, die zu folgenden Resultaten führen:

1. Der Schalldruck betrug unter 1000 Hz den 10^4-ten Teil des Reizes und nahm darüber schnell ab. Seine Grösse war weiterhin abhängig vom Applikationsort des Reizes.

2. In verschiedenen Experimenten wurde gefunden, dass Veränderungen am Unterkiefer die Schalldruckgrösse beeinflussen und dabei zugleich eine Schwellenverschiebung für Knochenleitung verursachen. Beide Effekte waren nach Grösse und Symptomen verschieden.

3. Bestimmte Veränderungen am Mittelohr hatten keinen messbaren Einfluss auf den Schalldruck, während sie die Luft- und Knochenleitungsschwelle jedoch beeinflussen. Es wurden folgende Schlüsse gezogen:

a. Der Unterkiefer spielt eine Rolle bei der Entstehung des Schalldrucks im Gehörgang, doch ist diese nicht so einfach wie sie gewöhnlich dargestellt wird.

b. Klinische Messung des Schalldrucks im Meatus, um daraus die Funktion des Schallleitungsapparates zu bestimmen, ist keine zuverlässige Methode.

c. Änderungen des Schalldrucks im Gehörgang müssen nicht mit entsprechenden Änderungen der Knochenleitungsschwelle einhergehen, während dies umgekehrt ebensowenig der Fall sein muss. Dies ist nach der in Kapitel VIII beschriebenen Betrachtungsweise verständlich.

Das 6. Kapitel handelt von der *Knochenleitungsschwelle bei Mittelohrerkrankungen.* Auf Grund der Tatsache, dass experimentelle Veränderungen am Mittelohr die Knochenleitungsschwelle beeinflussen können, wird darauf hingewiesen, dass dies bei pathologischen Erscheinungen ebenso der Fall sein kann. Die Ergebnisse eigener Nachforschungen nach dem Vorkommen verschiedener Formen von Knochenleitung werden besprochen:

1. In verschiedenen Fällen wurde ein Knochenleitungsverlust mit ansteigender Kurve gefunden. Es wird darauf hingewiesen, dass dieser Verlust eine Folge zunehmender Versteifung des Leitungsapparates sein könnte. Bei einzelnen Patienten mit einem derartigen Verlust konnte nachgewiesen werden, dass dies Symptom auf einem Mittelohreffekt beruhte, da es bei Behandlung verschwand.
2. Kurven der Knochenleitungsschwelle mit einer den mittleren Frequenzen vorgelegenen Depression (Carhart notch) können nachgewiesenermassen ausser durch Otosklerose auch durch entzündliche Prozesse entstanden sein. Es wurde gefunden das diese Depression durch Behandlung zum Verschwinden gebracht werden kann.
3. Auf verschiedenen Audiogrammen wurde eine supranormale Knochenleitungsschwelle gefunden, hauptsächlich bei Kindern.

Die Knochenleitungsschwelle bei Otitis media, Tubotympanitis, chronischen Entzündungsprozessen und bei Otosklerose werden besprochen. Von Otosklerose ist bekannt, dass dabei die Mittelohrabweichung einen muldenförmigen Knochenleitungsverlust verursacht (Carhart notch). Es wird versucht, diesen Verlust als eine Folge des Ausfalls der Verstärkung der Kochlearflüssigkeitsschwingung durch der Schwingung der Gehörknöchelchen zu erklären.

Auch bei anderen Mittelohrerkrankungen kann jedoch durch die Abweichung am Schallleitungsapparat ein ziemlich grosser Knochenleitungsverlust entstehen. Dies wird demonstriert an Beispielen von Patienten, bei denen sich die Knochenleitung durch Behandlung bedeutend besserte.

Im 7. Kapitel wird an erster Stelle *die Entwicklung der Knochenleitungstheorie* besprochen. Verweilt wird bei dem Werk von Mach, Lucae, Politzer, Bezold, Brünings und Runge. Anschliessend kommen die Untersuchungen von Herzog, Krainz, von Békésy und E. Bárány, die die Grundlage der heutigen Theorie bilden, an die Reihe. Den Schluss bilden die Untersuchungen und Veröffentlichungen der jüngsten Vergangenheit, bei deren Besprechung die neuesten Knochenleitungstheorien von Kraus und von Langenbeck kritisiert werden.

Es wird eingegangen auf die zur Zeit *allgemein anerkannte Knochenleitungstheorie,* wie sie in Lehrbüchern bezeichnet wird. Man nimmt 3 Arten von Knochenleitung an: 'Inertia'-knochenleitung (besonders bei niedrigen Frequenzen), 'Kompressions'-knochenleitung (besonders bei hohen Frequenzen) und 'Knochenleitung beim Wege der Luftleitung'. Diese drei Formen der Knochenleitung sollten in gegenseitigem Zusammenwirken die Empfindung zustandebringen.

Im 8. Kapitel wird auf die *Mängel der heutigen Knochenleitungstheorie* hingewiesen. Weder die klinischen Phänomene der Knochenleitung, noch die in den vorigen Kapiteln behandelten experimentellen Phänomene können mit dieser Theorie zureichend erklärt werden.

Es wird daher eine *neue Betrachtungsweise des Knochenleitungsmechanismus* vorgeschlagen. Statt mit interferierenden 'Wege' der Knochenleitung zu arbeiten wird der Knochenleitungsmechanismus gemäss den für ein komplexes Schwingungssystem geltenden Prinzipien betrachtet. Mit dem knöchernen Schädel werden bei Knochenleitung nämlich alle Teile des Kopfes in Schwingung gebracht, sodass man von einem Komplex gekoppelter Schwingungssysteme sprechen kann. Die klinischen und experimentell gefundenen Erscheinungen der Knochenleitung müssen als Folge einer Veränderung der Eigenschaften dieser Systeme (d.i. Mittelohr, äusseres Ohr, Unterkiefer usw.) angesehen werden. Diese Änderungen verursachen Umstellungen in den gegenseitigen Verhältnissen von Impedanzen und Koppelungen, was auf die Schwingung der Kochlearflüssigkeit zurückwirkt.

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STELLINGEN

I

Aangezien de beengeleidingsdrempel door veranderingen aan het middenoor niet onbelangrijk beïnvloed kan worden, dient het beengeleidingsaudiogram bij middenooraandoeningen met de nodige reserve als criterium voor de perceptiefunctie van het oor gebruikt te worden.

II

De proef van Gellé en de occlusieproef mogen niet, zoals zeer veel geschiedt, worden opgevat als specifieke onderzoekmethoden op otosklerose.

III

De lateralisatie in het slechtste oor bij de stemvorkproef van Weber bij geleidingsdoofheid wordt door de moderne theorieën, die de oorzaak zoeken in een faseverschil tussen de cochleaprikkels, onvoldoende verklaard.

B. Langenbeck: *Ann. d'Oto-laryng. 71*, 509, 1954.
Acta oto-laryng. 50, 406, 1959.
S. Tarab: *Rev. Laryng., Otol., Rhinol. 79*, 1223, 1958.

IV

Afkoeling van het fibrillerend zoogdierhart is in vergelijking met de bekende chemische en electrische middelen een zeer succesvolle methode om defibrillatie te bewerkstelligen.

M. N. J. Dirken, F. Gevers, H. Heemstra,
E. H. Huizing: *Circ. Res. 3*, 24, 1955.

V

De defibrillerende werking van temperatuursverlaging vindt zijn oorzaak in een sterke verlenging van de refractairtijd van de hartspiervezels.

E. H. Huizing, Jw. van den Berg, M. N. J. Dirken:
Acta Physiol. Pharmacol. Neerl. 4, 46, 1955.

VI

Cellen met relatief grote kernen zijn in het algemeen het meest radiosensibel; dit vindt zijn oorzaak in het feit, dat nucleoplasma in vergelijking met cytoplasma in mindere mate door zijn enzymsystemen beschermd is tegen de inwerking van bij bestraling vrijkomende actieve zuurstofradikalen.

VII

Bij verlammingen door kaliumdepletie ontstaat een daling van de spiervezelpotentiaal, die niet berust op een verandering van de kaliumconcentratiegradient doch op veranderingen in de spiereiwitten.

K. Panman: Diss. Gron., 1958.

VIII

Bij patienten met recidiverende iridocyclitis of chorioditis is het juist om — althans wanneer geen andere etiologische momenten zijn gevonden — ook bij „klinisch rustige" tonsillen tonsillectomie te doen.

IX

Om bij snelle of grote bloedtransfusies het gevaar van citraatintoxicatie te vermijden is het door T. Huizinga aangegeven gebruik van gedialyseerd citraatbloed het meest ideaal.

X

Onderzoekingen op het gebied van synaesthesieën, zoals de „audition colorée", zullen weinig constante uitkomsten kunnen geven, aangezien synaesthesieën sterk bepaald worden door cultuurervaring.