MASTER

An artificial head for acoustical measurements on earphones

Dinnissen, P.H.M.

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An artificial head for acoustical measurements on earphones

by P.H.M. Dinnissen

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Of course I thank the staff and members of the group Telecommunication-A for their cooperation and support during the 11 months I have been working among them.
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1. Introduction

Untill some 20 years ago the measuring of acoustical properties of earphones did not present too many problems. This was mainly caused by the fact that the earphones of that time were only required to give a faithful reproduction of frequencies within the speech band (300 - 3500 Hz). Within this frequency band the real-ear response of a telephone could be measured with a reasonable degree of accuracy by determining its pressure response on a 6 cc coupler, a cylindrical cavity, the bottom of which was formed by the diaphragm of a (condenser-) microphone. The limitations of this method of calibration soon became obvious when it was applied to headphones intended to reproduce a wider frequency band. Particularly the acoustical impedance presented by the couplers appeared to differ considerably from the input impedance of an average human ear for frequencies above 2 kHz.

To eliminate this disadvantage several modifications were developed that deviated from the original couplers by their shape, by built-in air leaks and by the presence of one or more coupled cavities.

These "second generation artificial ears" were still anything but universally usable. One of their limitations remained the frequency band which, though considerably extended, was still insufficient for accurate calibration of, for instance, audiometer headphones and the modern headphones for music-listening. A second drawback was their being developed for measurements on the supra-aural type of earphones only.

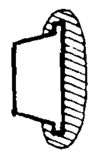
This report contains a discussion on some theoretical aspects of the measuring of earphone characteristics and on the acoustical behaviour of the human ear, as well as the description of a prototype of an artificial head which was built in order to obtain a more versatile measuring device for the acoustical properties of earphones.

2. Headphones

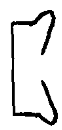
Headphones can roughly be subdivided into five classes considering their shape and the extent to which exterior sound is excluded.

1. Earphone, with an orifice terminating freely in front of the ear.

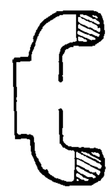
2. Headphone, fitting on the ear by means of a porous cushion.



3. Headphone pressed against the ear, usually referred to in literature as the supra-aural type.



4. Headphone fitting around the ear by means of a foamed-rubber or liquid-filled cushion, referred to as the circumaural type.



5. Earphone with an earpiece fitting into the earcanal, applied mostly in hearing-aids.

Of course many hybrid forms exist.

Factors of interest when studying the transmission of a signal from a source (e.g. an amplifier) to the eardrum when using earphones are:

- The transfer function of the earphone. This is the property to be measured.
- The transfer characteristic of the external ear.
- Changes in acoustical properties of the ear caused by the application of an earphone.
- Influence of the acoustical properties of the ear on the performance of the earphone

The latter three of these factors will be discussed in the next two chapters.

3. Transfer function of the external ear

The transmission of sound from the free-field to the eardrum is governed by two phenomena: diffraction by the head and pinna, and resonances in the outer ear.

3.1. Diffraction of the sound field by the head starts getting important at frequencies with a corresponding wavelength in the order of magnitude of the head dimensions, this is for f > 200 Hz. The results are an increasing sound pressure at the side of the head turned towards the sound source and a decreasing of the pressure on the other side. At still higher frequencies the sound field is further influenced by similar effects caused by the pinna. An illustration is given in fig.1. In the following paragraphs the transfer function of the ear will be regarded as a whole, including diffraction.

3.2. Resonances in the external ear.
The transfer function of the outer ear can be subdivided in two parts: from free field to earcanal entrance and from earcanal entrance to eardrum.

- Earcanal entrance to eardrum.
The latest and most reliable measurements on this part of the transmission path have been made in 1946 (ref. 28). The results are given in fig. 2. The pressure ratio as a function of frequency appears to be substantially independent of the azimuth and exhibits a broad peak of about 10 dB near 3500 Hz, probably caused by a $\frac{1}{4}\lambda$ resonance of the auditory canal. The appearance of other peaks at higher frequencies can reasonably be expected but no measurements have yet been made to confirm this. Considerable difficulties to be surmounted when trying to measure sound pressures at the eardrum with very narrow probes are probably responsible for this gap.

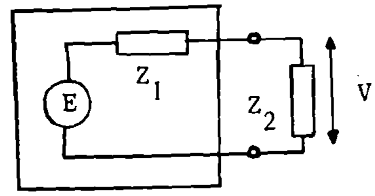
- Sound pressures at the earcanal entrance are much easier to measure and fairly complete data have been published on this subject (ref. 22). The average pressure level at earcanal entrance versus free-field pressure as a function of frequency and azimuth (average of 9 subjects) is shown in fig. 3.

Although the dependance on the angle of incidence is obvious the general shape of the curves remains more or less the same at different azimuths.
The most remarkable aspect of this part of the transfer function however is best revealed by showing the curves of the individual subjects, as is done in fig. 4.
The considerable differences between the individual curves is further illustrated by comparing the frequencies at which corresponding maxima and minima occur, as is done for 6 subjects in fig. 5.
An indication for the cause of these differences is given by fig. 6, suggesting different transfer functions to be retraceable to differences in geometry of the pinna.
There is one more factor determining the acoustical behaviour of the outer ear. Resonances in the ear are caused by the shape of the auricle and the ear canal, but their magnitude is also determined by the acoustical impedance of the skin and the equivalent impedance of the eardrum.

Measurements at frequencies above 700 Hz have shown the skin impedance to be almost infinite compared to the eardrum impedance (absorbtion factor less than 4%). The impedance at lower frequencies is less important as the pressure distribution is uniform anyway.

Published data on the eardrum impedance are still very incomplete. Even fairly recent investigations (ref.32) have yielded no results beyond 2 kHz. The available data have been plotted in fig.7.

4. Acoustical impedance of the ear



When representing the earphone - ear system by a source with internal impedance Z_1, terminated by an external impedance Z_2 the influence of Z_2 on the output $V = E \dfrac{Z_2}{Z_1+Z_2}$ is easily recognized.

Unfortunately the measuring of the input impedance of human ears is anything but easy and complete data have hitherto only been published on the impedance presented to supra-aural earphones (ref.8). An example of the impedance viewed through two different earcaps is shown in fig.8.
The electrical analogue network for one of these cases is reproduced in fig.9. The value of the components can vary by a factor of about 2, depending on the model of earcap and in any case the obtained values only represent averages measured on a number of subjects.

Quite apart from uncertainties in the data themselves it is by no means certain that these data are of any use when trying to calculate the impedance presented to other types of earphones. As has clearly been revealed by a photograph published by Delany (ref.8, plate 1) the application of a supra-aural earcap causes the volume entrapped by earcap and pinna to be split up into a number of coupled cavities so that the resonance pattern in the ear can differ considerably from the free-field situation.
Ignoring this effect something at least can be said about the impedance presented to the different types of headphones and the contribution of the impedance of the ear itself:

Class 1: The load impedance of this class of earphones is almost entirely determined by the very large air leak that can be symbolized by a very small resistor shunting the ear impedance.

Class 2: The same applies to this class.

Class 3: The available data apply to the supra-aural class.

Class 4: In the case of the circumaural headphones the load impedance is determined to a considerable extent by the enclosed volume (some 100 cc) symbolized by a large capacitor shunting the ear impedance.

Class 5: For the hearing-aid type of earphones the situation is altogether different, as the load impedance is formed by a part of the auditory canal and the eardrum.

5. The artificial head

As disadvantages of existing artificial ears have been mentioned their (in most cases) limited frequency range and their unfitness to measure other headphones than the supra-aural type under realistic conditions. When trying to design an artificial ear for application on other headphones one of the first problems encountered is the lack of data on the acoustical impedance and a part of the transfer function of human ears.

Another important factor to be considered is that the average of the acoustical properties of a number of human ears is something completely different from the acoustical properties of an average human ear, as has clearly been demonstrated for the transfer function in chapter 3.

All these considerations have led to the decision to build an artificial ear, or rather a complete artificial head with physical dimensions corresponding with the dimensions of an average human ear and head, made of a material with acoustical properties comparable to those of human skin. The design of such a head can be divided into three parts:

5.1 The head

Because all measurements on the acoustics of the human ear have been made on living subjects the effects of head-diffraction form an inseperable part of, for instance, the transfer function of the ear. The presence of a head is therefore essential when calibrating the final artificial ears in a free sound field.

The purely mechanical properties of headphones are another point of interest (e.g. influence of head breadth on the force of application exerted by the spring band etc) so the dimensions of the head should preferably be adjustable. A number of data on the dimensions of human heads are listed in appendix 1.

5.2 The auricle

The great influence of the pinna on the response of the ear has been demonstrated in chapter 3. For the sake of universality of the measurements and also for being able to determine the capability of, for instance, circumaural headphones to house auricles of different sizes it is desirable to provide the artificial head with a number of interchangeable pinnae, although the impossibility to determine the response of a headphone on any

particular ear cannot be avoided.
The average values of height and breadth of the auricle are included in appendix 1, as well as some data on auricle dimensions as a function of age, but more detailed information, particularly about dimensions of the concha (inner cavity of the pinna) could not be found.
It was therefore decided to produce replicas of existing human ears.

5.3 The ear canal

The human ear canal consists of a more or less cylindrical tube, some 22 millimetres in length and with a diameter of about 8 millimetres.
The canal wall can be regarded as acoustically rigid.
Considering the lack of data on the eardrum impedance a termination of the artificial canal by a simple RC - section seemed the most appropriate.
The extent to which this is an approximation may be concluded from fig.7, showing the eardrum impedance as well as the the impedances of a cavity of 0,6 cc and a resistance of 360 acoustical ohms.

6. Prototype of the artificial head

6.1 Description

The head itself was cast in a gypsum female mould of the original head, which was modelled in clay. Head dimensions correspond with the average values for a male head from appendix 1.
The material is a white silicone rubber (Silastic "E" RTV, manufactured by Dow Corning), supported by a layer of fiber-reinforced polyester.

The left auricle is a dummy, the right-hand one is a removeable replica (made in the same silicone rubber from a gypsum cast) of the author's ear which happened to have an about average shape, although the dimensions are slightly above average (69 mm in length).

A drawing of the artificial ear canal, which is made of brass, is reproduced in fig.10. It consists of a cylindrical tube with an average length of 22 millimetres. The angle of 30° between canal axis and the perpendicular on the microphone diaphragm was chosen in view of the available space within the head and because it is a better approximation of the eardrum position in real ears.
The canal is terminated by a condenser microphone (B&K 4134) and a 0,6 cc cavity coupled to the tube by means of a narrow slit. The width of the slit was adjusted untill the $\frac{1}{4}\lambda$ resonance peak in the transfer function of the canal was about 10 dB high. The resulting value appeared to be about 0,05 mm, which agrees with the theoretical value for such an impedance having a resistance of about 350 acoustical ohms (ref.4, chapter 5). Finally the canal length was reduced by about 3,5 millimetres to account for the part of the canal supplied by the pinna replica. (Fig.10 shows the original length).

6.2 Performance

(All measurements have been made under anechoic conditions)
Fig.11 shows the response curve (microphone pressure to entrance pressure) of the ear canal before the 3,5 mm were chopped off. Sound pressure at the canal orifice was kept constant by means of a reference microphone placed next to it and included in a feed-back loop to the loudspeaker. The finite distance between this microphone and the canal entrance (about 20 mm) probably causes the irregularities at frequencies above 5 kHz in the original recording, which is reproduced in fig.12.

The free-field response of the complete artificial head, shown in fig.13, was measured in an anechoic room with the head resting on a support which was concealed acoustically by hanging a jacket around the head's shoulders. The curves were obtained by subtracting the frequency characteristic of the loudspeaker (a dome tweeter) from the original recordings, followed by some visual smoothing. In two or three cases, notably at negative azimuths, this latter process amounted to "educated guesswork" because of the irregularities in the curves, probably caused by interference of sound waves around the head. Two of the original recordings, including the very worst one of these cases, are reproduced in fig.14.
The influence of small changes in the angle of incidence on the detials of the curves was considerable. It appeared practically impossible to make a recording, remove the head and put it back in about the same position and measure exactly the same curve again.
Measurements were also made with the head wearing a wig. The differences, though perceptible, were not very great. An example is given in fig.15.

In order to obtain a complete set of data on the performance of the artificial head measurements have yet to be made with a probe microphone of the sound pressure at the earcanal entrance. This is also necessary for being able to determine the actual transfer characteristic of the earcanal, which need not necessarily be the same as the free-field response of fig.11. The measurements also have to be extended below the 900 Hz that were the cutt-off frequency of the dome tweeter. Below some 200 Hz, incidentally, any free-field curve measured on the artificial head can hardly be something else than a straight line on 0 dB level.

6.3 Comments

Although at this stage it is difficult to say anything definitive the conclusion seems justified that the artificial head and ear behave acoustically like their human counterparts. When some practical problems mentioned in the next chapter will have been solved the head will, for many types of earphones, probably be a more accurate measuring device than the existing artificial ears. The measuring procedure, however, will be much more complicated as it involves the subtraction of one of the free-field curves of the artificial head from the curve measured with the head wearing an earphone.
A problem this may lead to is discussed in chapter 8.

7. Remarks and suggestions for further research

A number of facts relating to the artificial head and to sound reproduction by earphones in general deserve further discussion and further research:

1. After the prototype of the head has been completely tested, measured and approved a version of the head with adjustable breadth and height and, if desired, with two active ears has still to be developed.

2. The response of an earphone as a function of frequency is determined by subtracting the free-field transfer characteristic of the head from the curve measured with the head wearing the earphone. Because the external ear can be regarded as a linear system there is no special need for measuring at the eardrum position. As long as the ear keeps behaving like its human original the measuring microphone can in principle be located almost anywhere within the ear. Of course it always has to be in the same place.

3. Once the free-field response of the ears in the artificial head has been determined the presence of at least a part of the head is no longer necessary for the measuring of earphone characteristics. In fact the missing of some regions of the head is inevitable if one wants to be able to decrease the head dimensions. Nor is a fully detailed face essential. Of course a complete head is still needed for the calibration of any new auricles.

4. As long as one homogeneous material is used it is impossible to produce realistic auricles with mechanical properties perfectly matching those of real ears. As a result the measuring circumstances for supra-aural earphones are probably less realistic with the artificial head than they are with the latest models of existing artificial ears. A perfect simulation of the mechanical properties of the human head is very difficult to obtain anyway (flexibility and elasticity of the skin and the flesh underneath as a function of the position around the ear).

5. The flexibility of the earcushions of some circumaural earphones is to a perceptible degree dependent on the temperature. Whether the temperature difference of about 15°C between a human head and the artificial head causes any differences between measuring results and real-ear response (as a result of poor sealing and consequently worse bass response) deserves being investigated.

6. Reasoning analogously one might investigate whether the head ought to be supplied with a wig.

7. Distorsion measurements with the artificial head are almost impossible because the relation between amplification or attenuation of the fundamental frequency and any of its harmonics is a very complicated function of the frequency.

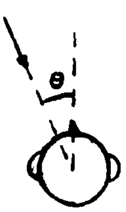
8. A final point for further research is whether the use of a different auricle causes any serious differences in the measured earphone characteristic (head+earphone response versus head free-field response, both of them measured, of course, with the same auricle each time). If so, the actual earphone characteristic will have to be determined by taking the average of the data obtained with several auricles.

8. Requirements of headphones

Although this subject need not necessarily concern a designer of a measuring tool it is nevertheless an interesting point of discussion and a perfect illustration of the uncertainty still existing about what the performance of an ideal headphone ought to be.
As examples the two kinds of headphones upon which the highest demands are made will be dealt with.

- Audiometer headphones

When applying a constant signal voltage to an ideal audiometer headphone the sound pressure at the eardrum should for all frequencies be equal to the sound pressure caused by a plane sound wave. As the effects of head diffraction do not occur when using headphones it might be desirable to have this loss compensated by a corresponding change in the frequency characteristic of the headphones.
The next point of discussion is the kind of head diffraction pattern to be simulated, in other words: the angle of incidence of the reference plane sound wave ($\theta = 0^o$ or $\theta = 90^o$). After all, the sound pressure in the ear is to a considerable degree dependent upon that angle. In any case it is not at all self-evident that an ideal headphone ought to have a flat frequency characteristic.



- Headphones for music listening

Similar difficulties arise when trying to fix requirements for music-headphones. Possible alternatives for the angle of incidence of the reference plane wave are:

$\theta = 0^o$, because of the instinct of a music listener to turn his head towards the sound source.

$\theta = 35^o$, referring to the usual arrangement of a pair of stereophonic loudspeakers.

$\theta = 90^o$, after all that is where the sound comes from when using headphones.

However, it remains doubtful whether the sound impression as caused by loudspeakers should be duplicated at all. This can be demonstrated as follows:

When listening to a piece of orchestral music reproduced stereophonically by loudspeakers one gets the impression of being seated at a distance of about 10 metres from the orchestra, which is distributed over a breadth of about 5 metres. When hearing the same music reproduced by headphones one gets the idea of standing on the place of the director, surrounded by the musicians. To obtain a sound impression conforming to this spatial impression of "presence" a slight emphasizing of high frequencies might be desirable.

All these considerations however are only partly valid because headphone and loudspeaker reproduction are essentially different as in the latter case each ear perceives the sound of both channels. Moreover the reproduction of very low frequencies (organ music) causes problems as these frequencies are felt rather than heard, a sensation that cannot be reproduced by headphones.

The conclusion to be drawn is that the artificial head can be developed into an accurate measuring tool for earphone characteristics but that a decision on the shape of an ideal earphone characteristic has yet to be made and that, at least for the time being, an agreement on the theoretical basis of such a decision is still missing.

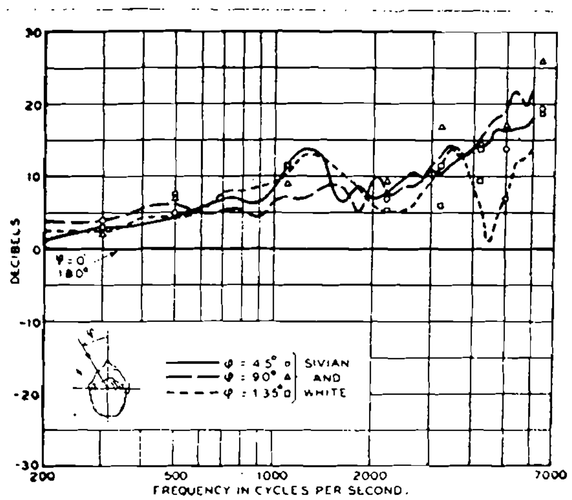


Fig.1. Ratio, in decibels, of sound pressure at left and right eardrum as a function of frequency and azimuth. Average for 6 observers. (From ref.29)

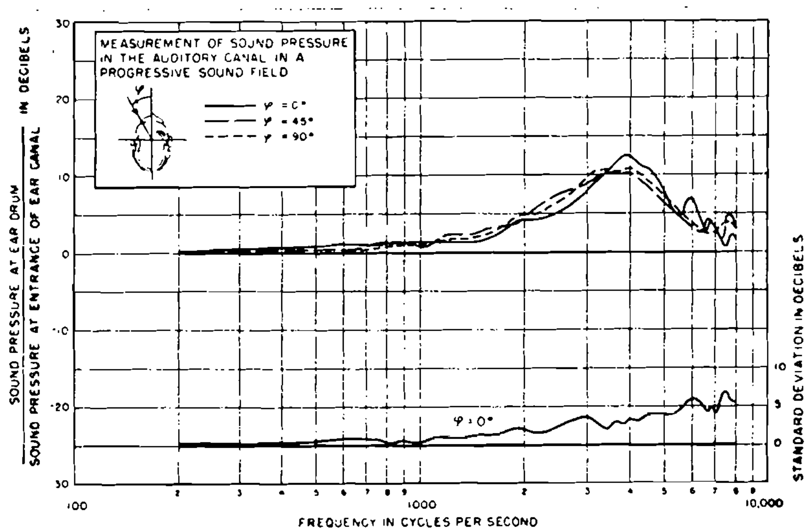


Fig.2. Ratio of sound pressure at the eardrum to sound pressure at earcanal entrance. Average of 6-12 male ears. (From ref.28)

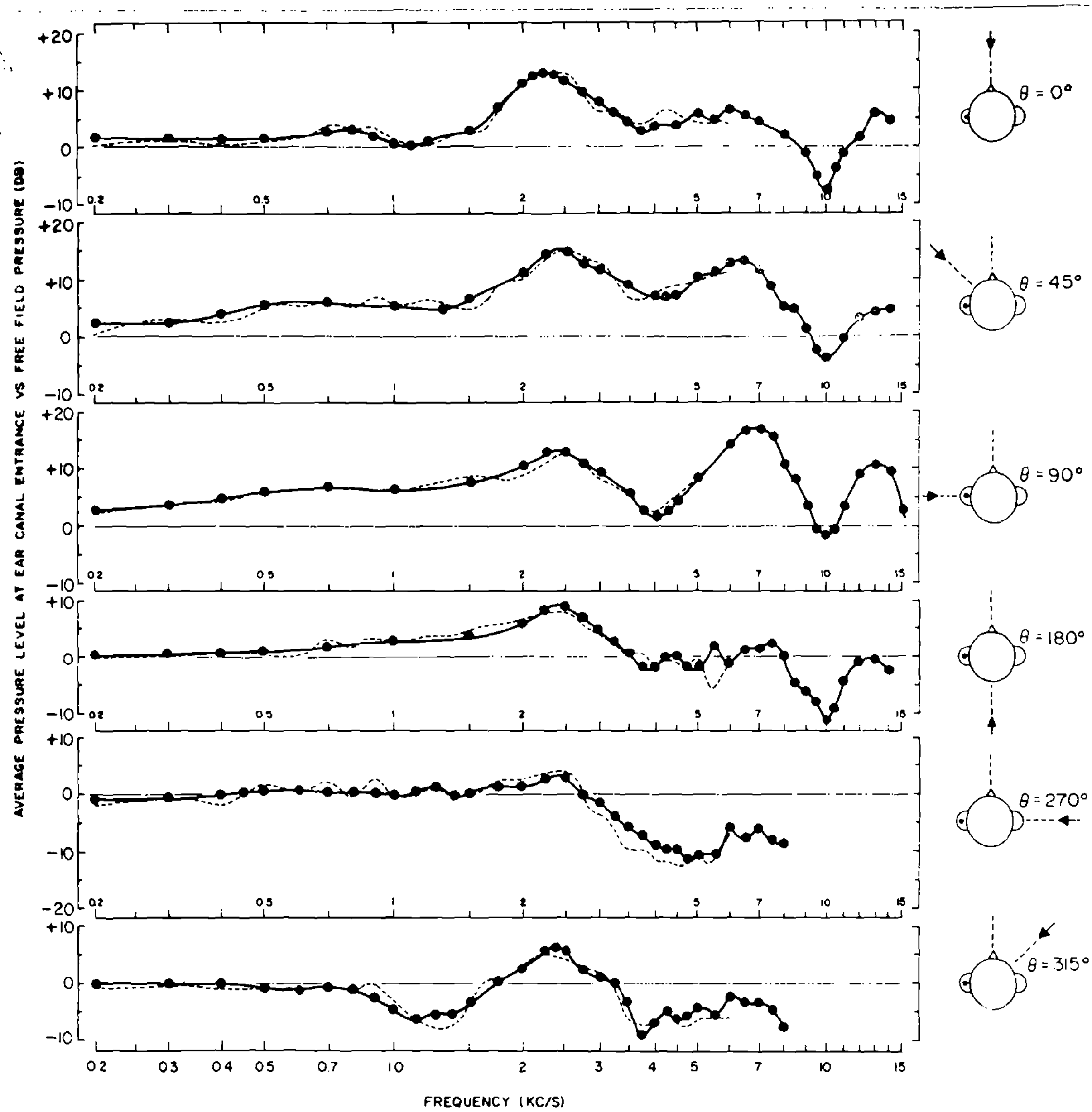


Fig.3. Pressure level at earcanal entrance versus free-field pressure in decibels. Average for 9 subjects. (From ref.22)

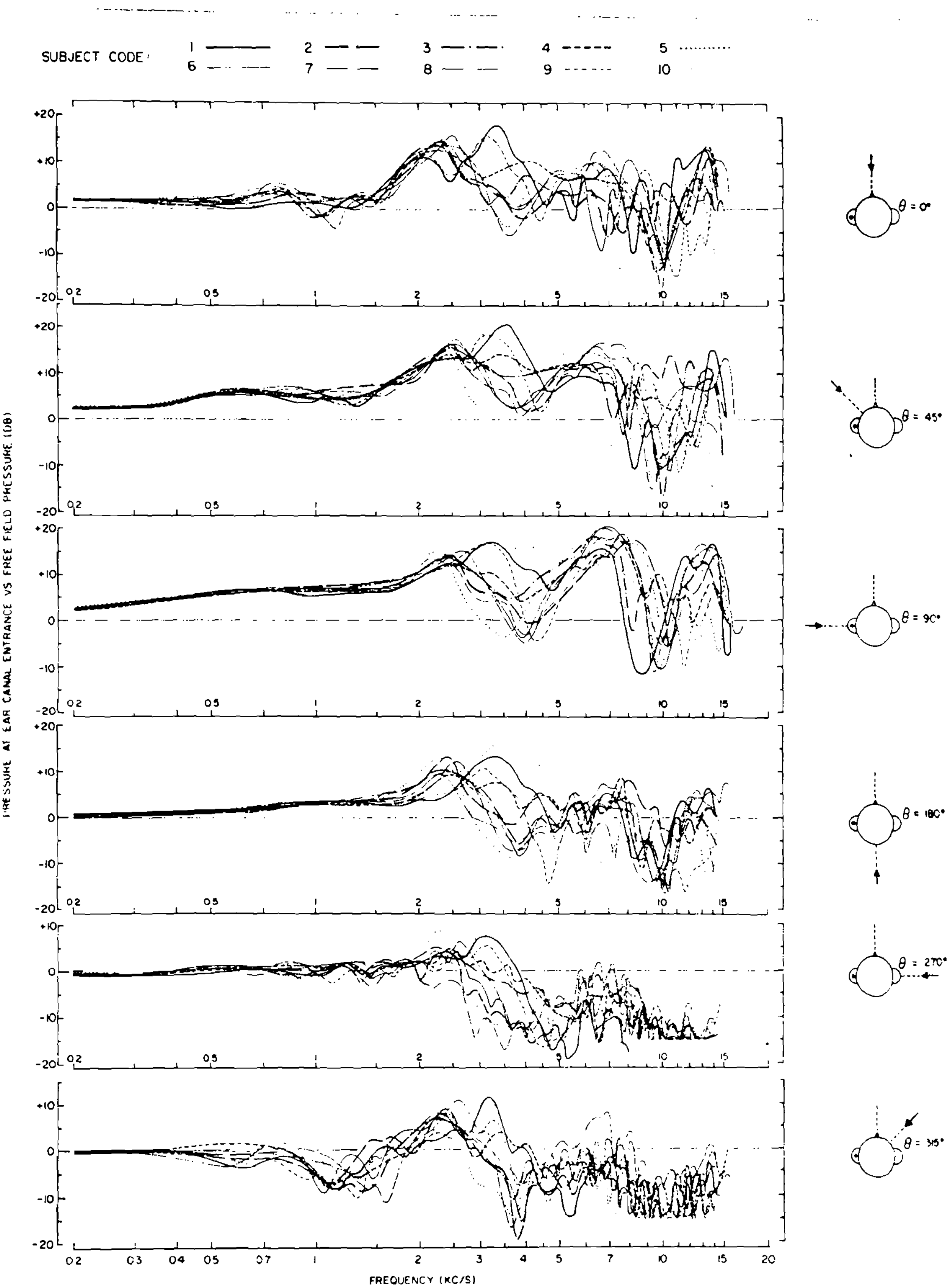


Fig.4. Pressure level at earcanal entrance versus free-field pressure, in decibels, for 10 individual subjects. (From ref.22)

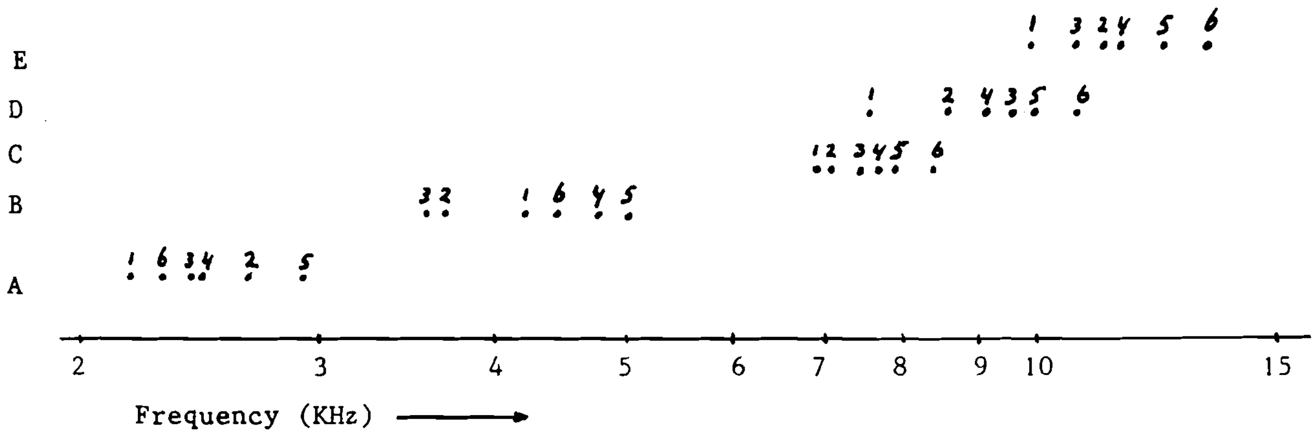


Fig.5. Frequencies at which corresponding features occur in free-field to earcanal-entrance transfer characteristics of 6 subjects. Numerals indicate subject. (From ref.24)

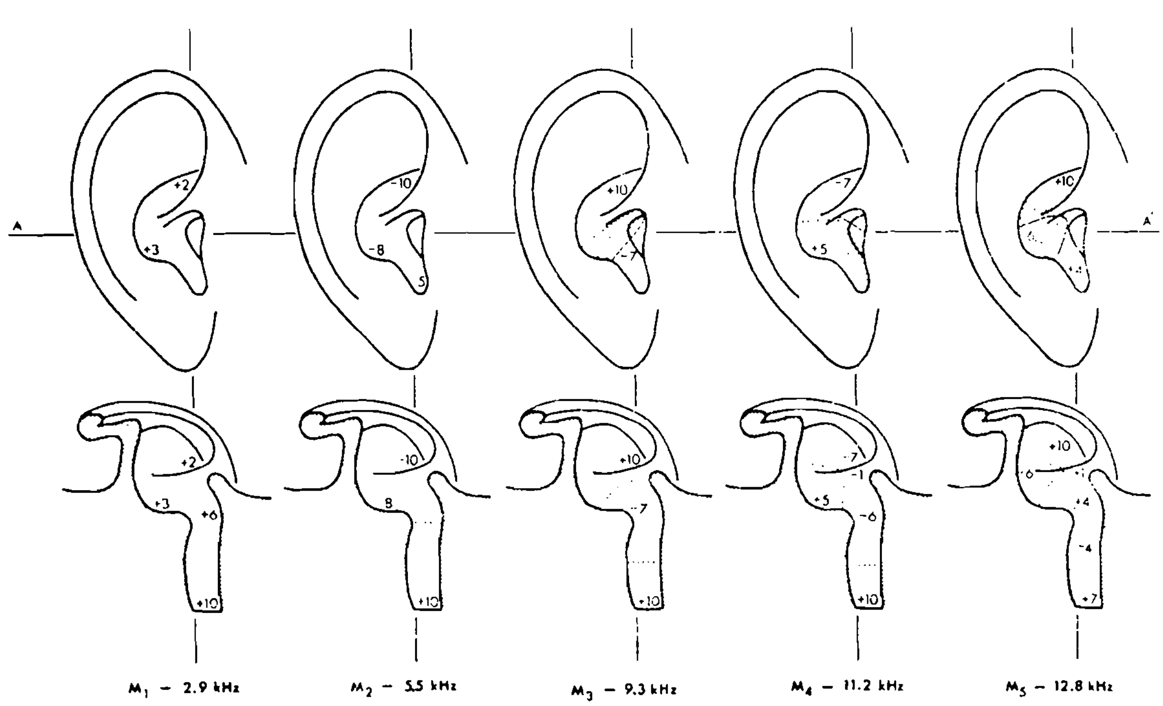


Fig.6. Pressure distribution in external ear replica with hard-wall eardrum at five peak frequencies. Dotted lines and shaded areas show position of nodal surfaces. Numerals give relative pressure, signs (+,-) indicate approximate phase. (From ref.24)

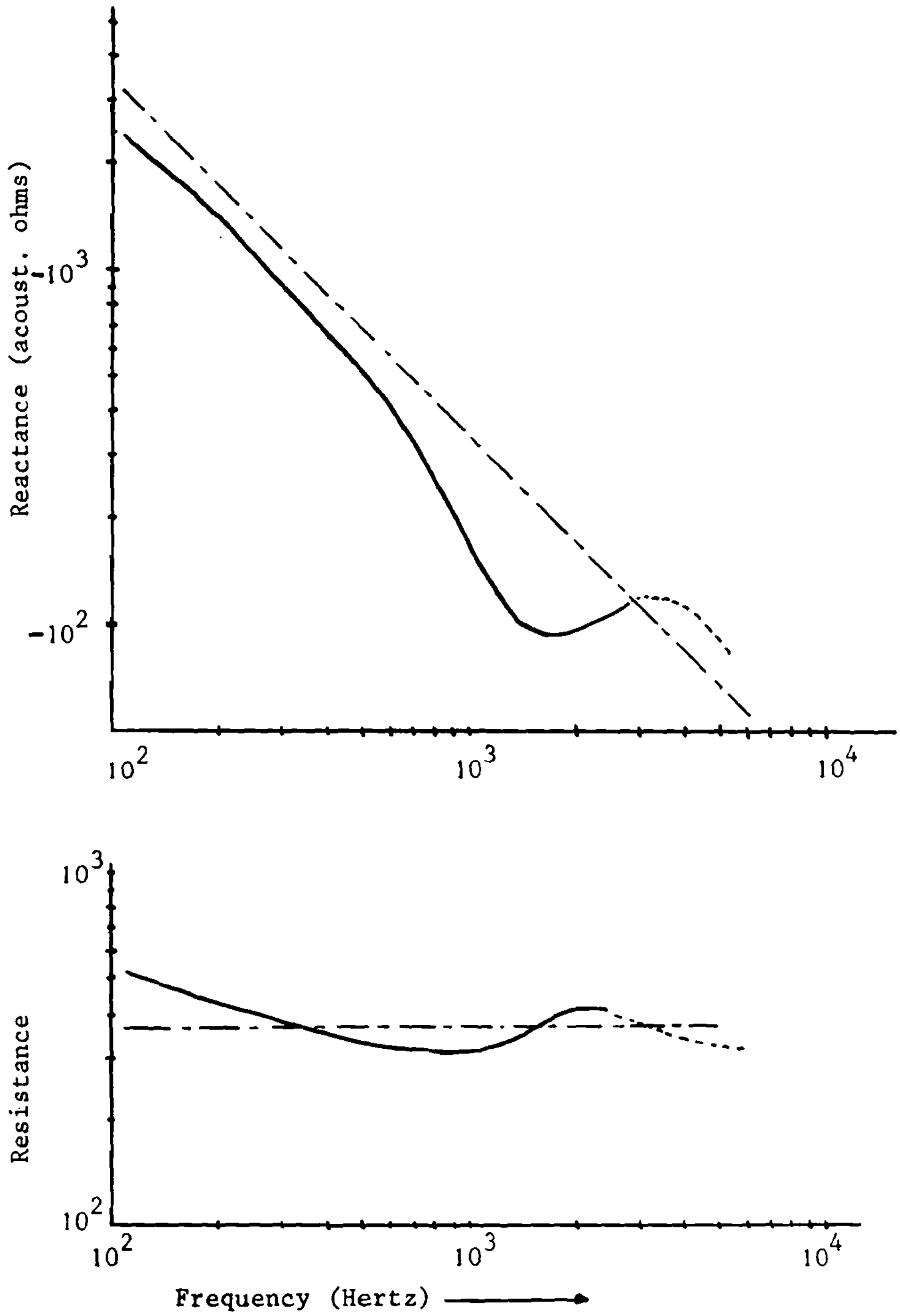


Fig.7. Impedance at the eardrum (solid lines, adapted from ref.32) and impedance of a 0.6cc cavity and a resistance of 360 acoust. ohms in series (dash-dot lines).

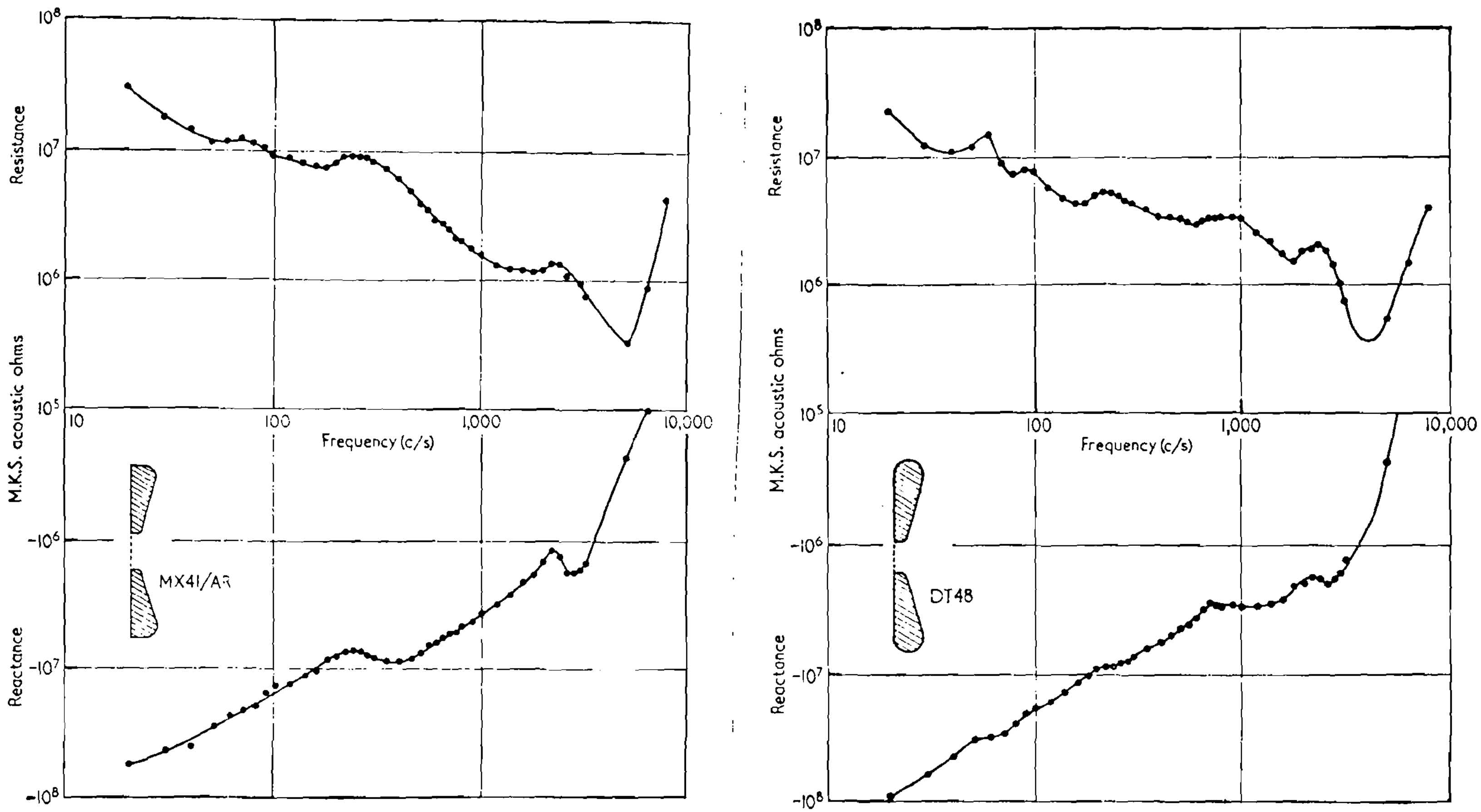


Fig.8. Impedance of the human ear viewed through aperture of ear-cushions of two supra-aural earphones (From ref. 8)

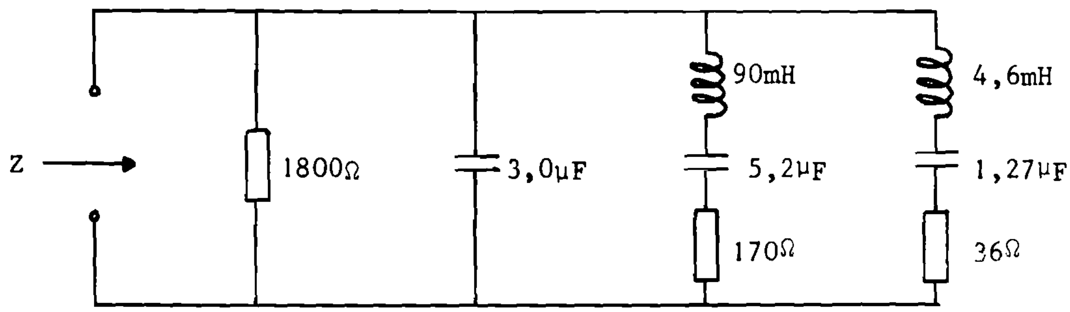


Fig.9. Electrical analogue network for impedance viewed through MX41/AR earcap. (From ref.8)

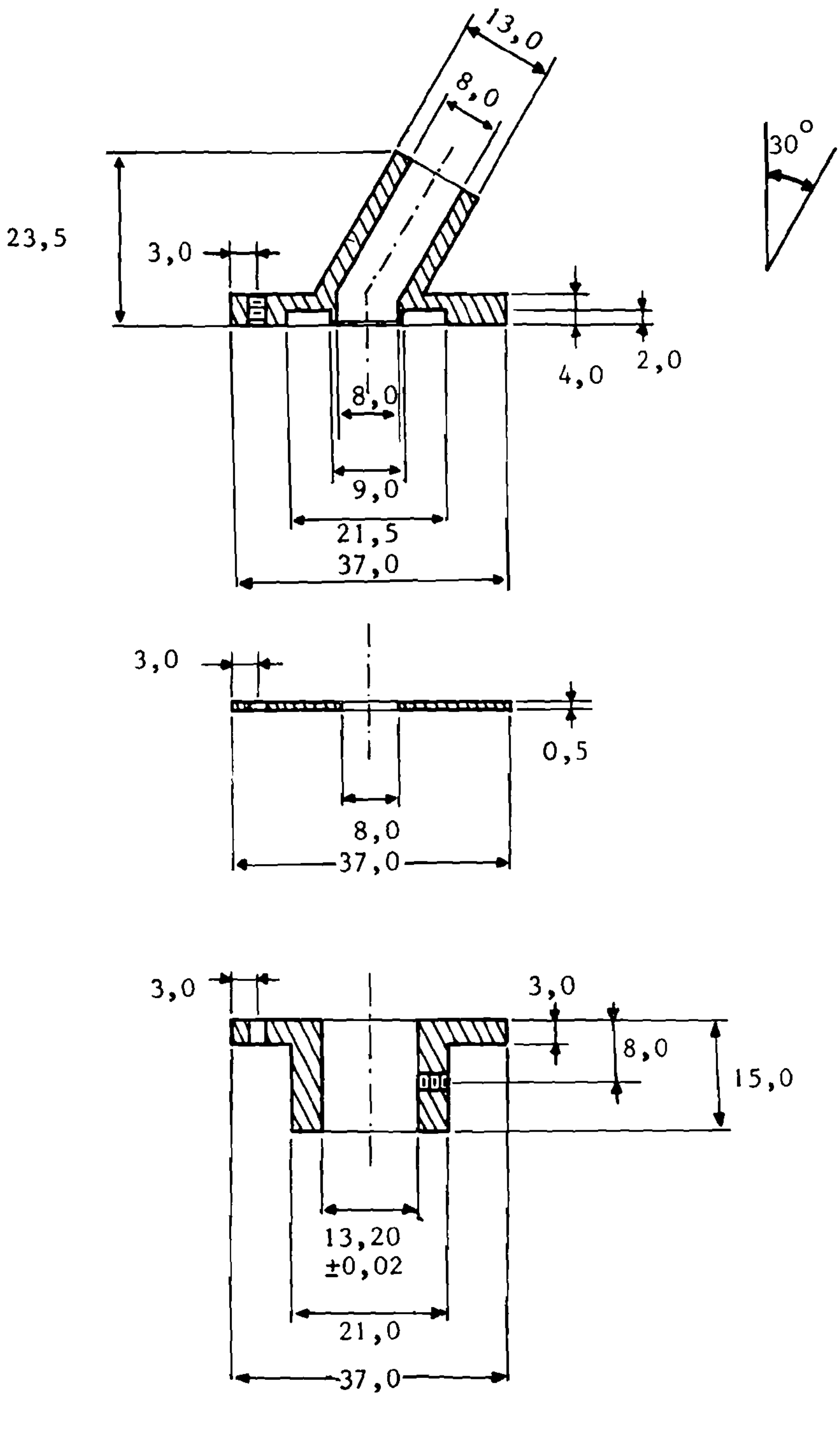


Fig.10. Artificial ear canal, longitudinal section.
Dimensions in millimetres.

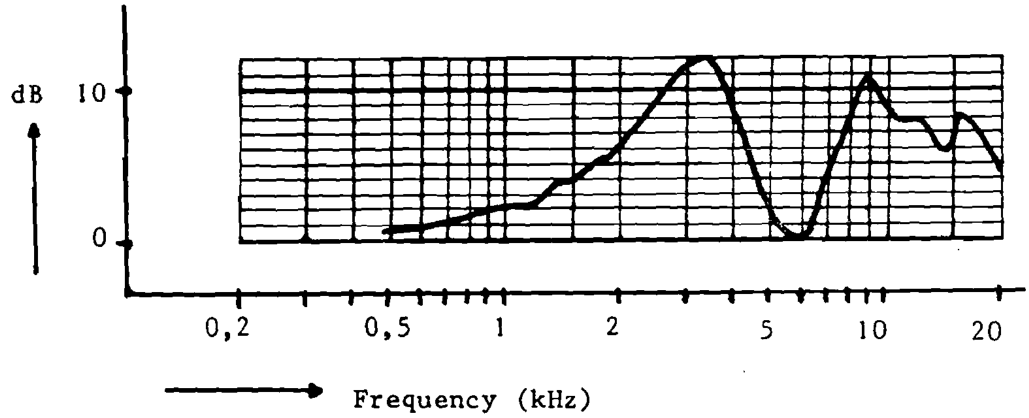


Fig.11. Microphone pressure versus entrance pressure of the artificial ear canal, measured in a free sound field.

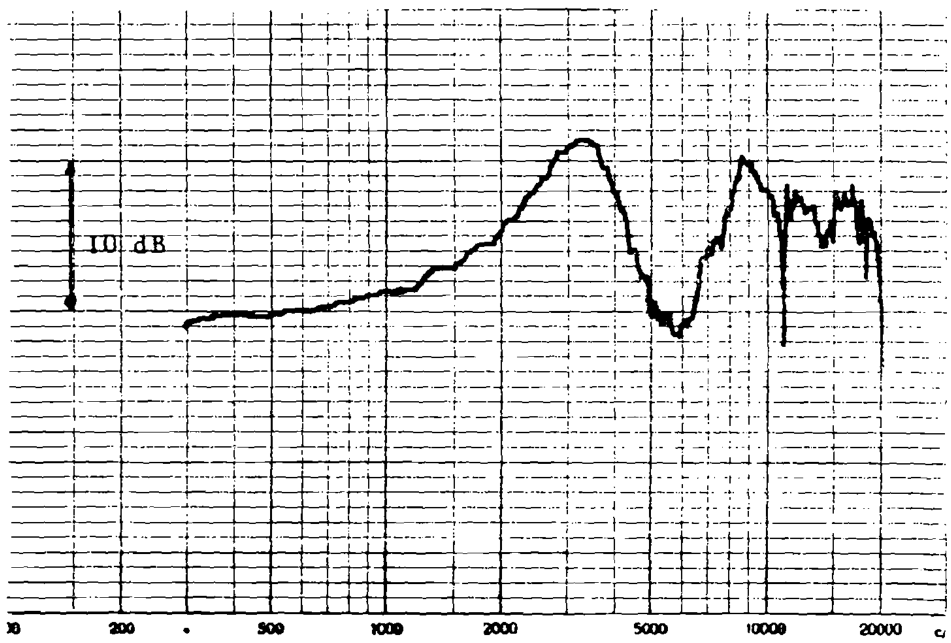


Fig.12. The original recording of fig.11.

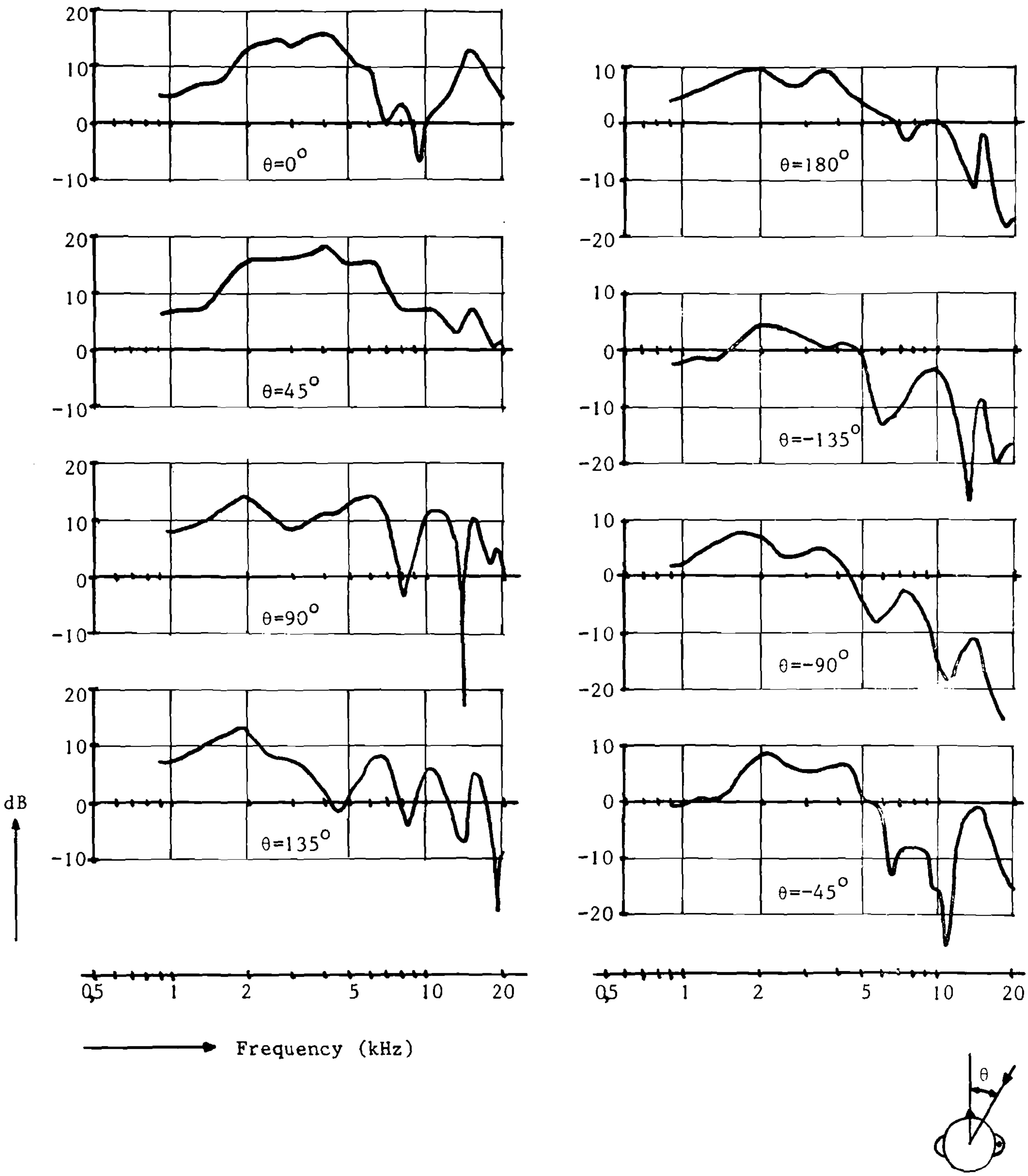
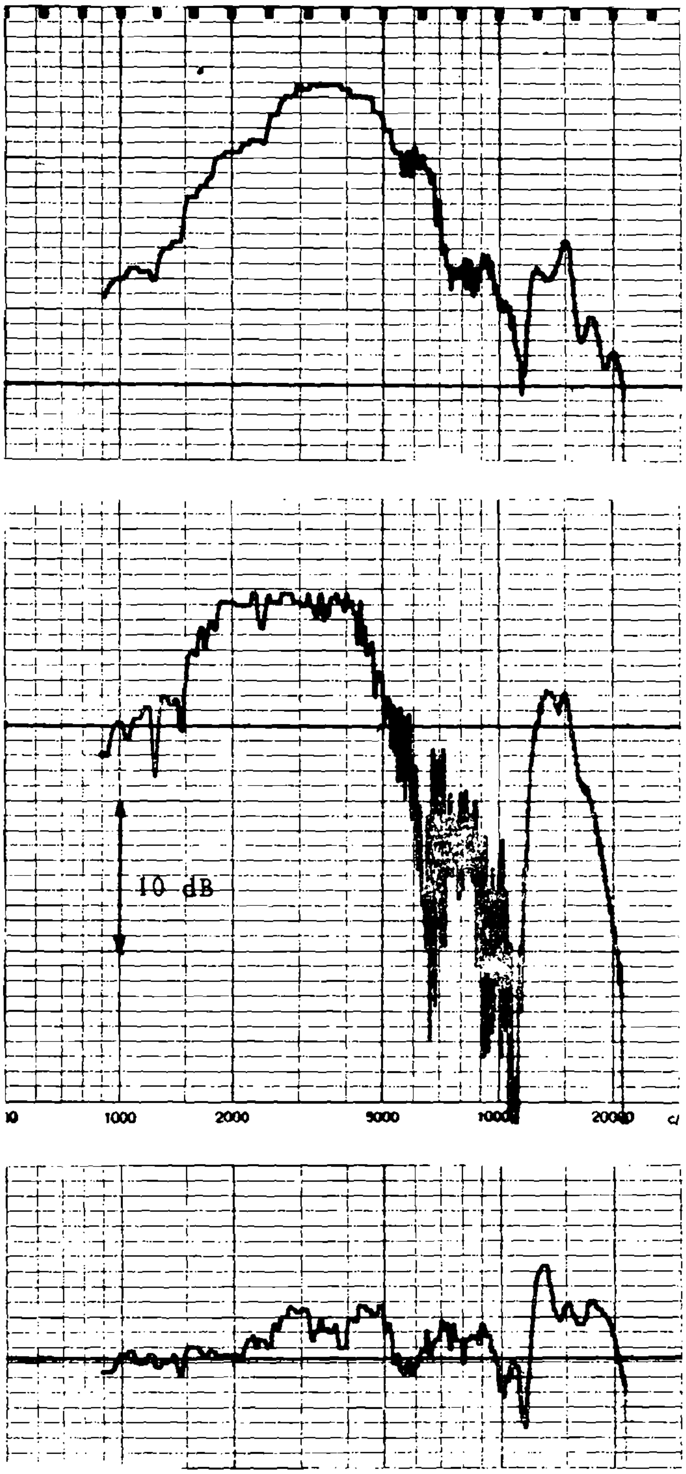


Fig. 13. Free-field response of the artificial head (microphone pressure versus free-field pressure, in decibels) as a function of frequency for eight azimuths.



$\theta = 45^{\circ}$

$\theta = -45^{\circ}$

The loudspeaker's frequency characteristic that has to be subtracted from the curves.

Fig.14. Two of the original recordings of the curves in fig.13.

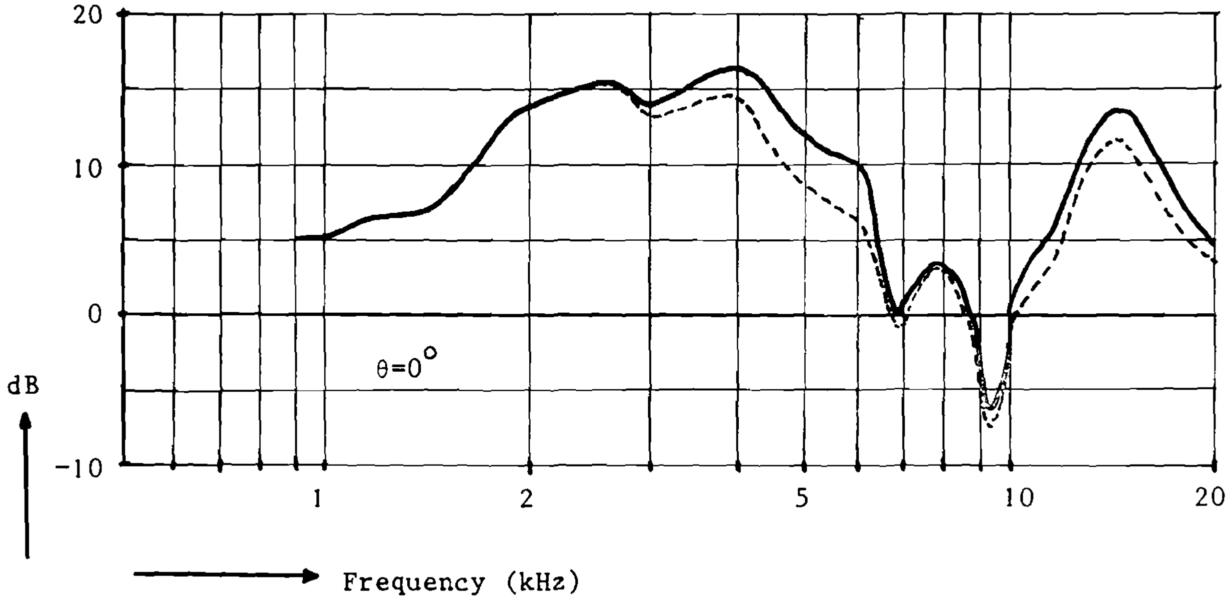
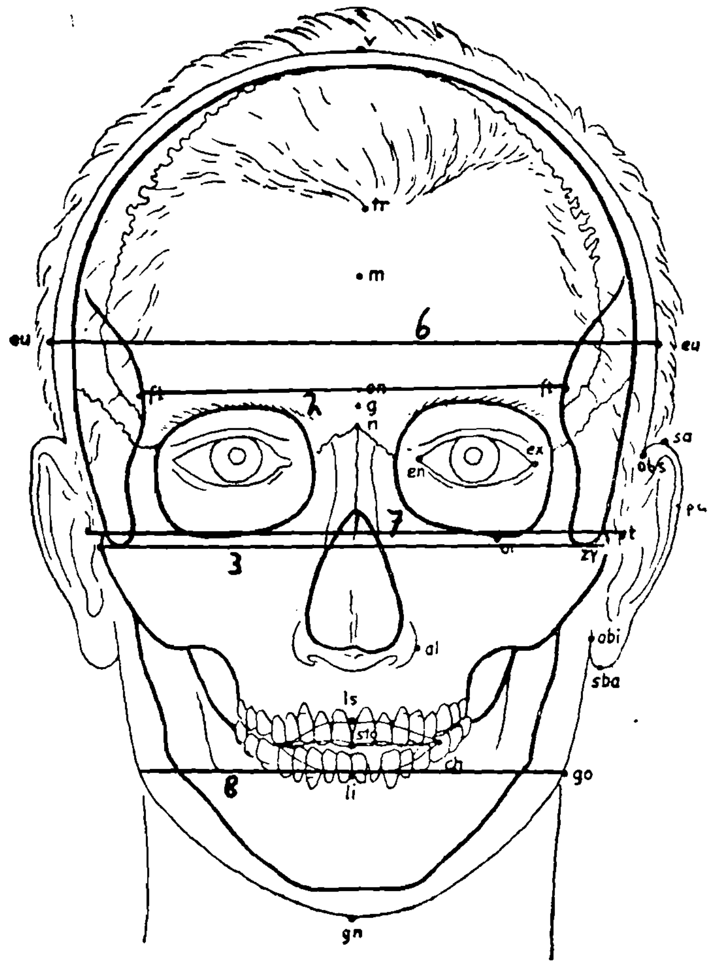


Fig.15.Free-field response of the artificial head without (solid line) and with (dashed line) a wig.

Appendix 1.

Data on the dimensions of 150 male and 89 female Dutch human heads.
All dimensions in millimetres.
M : mean value.
S : standard deviation.
S_m: standard deviation of the mean value itself.
Numbers refer to drawings on next page.
Average age of subjects : about 60.

	men			women		
	M	S	S_m	M	S	S_m
1. greatest head length	191,8	7,4	0,62	185,6	15,9	1,7
2. smallest forehead breadth	107,3	7,3	0,59	104,6	6,4	0,69
3. distance of zygomatic arches	138,1	7,4	0,61	130,0	7,1	0,76
4. tragion - head top	123,8	8,7	0,73	120,5	9,5	1,05
5. auricle breadth	39,0	3,3	0,28	36,7	3,1	0,34
6. greatest head breadth	154,6	6,6	0,55	148,0	5,6	0,60
7. tragion-tragion	136,8	9,3	0,77	130,3	7,9	0,85
8.	104,0	9,3	0,78	98,0	7,5	0,82
9. total head height	224,7	18,4	1,5	213,1	16,1	1,7
10. auricle length	66,8	4,8	0,39	62,9	4,6	0,50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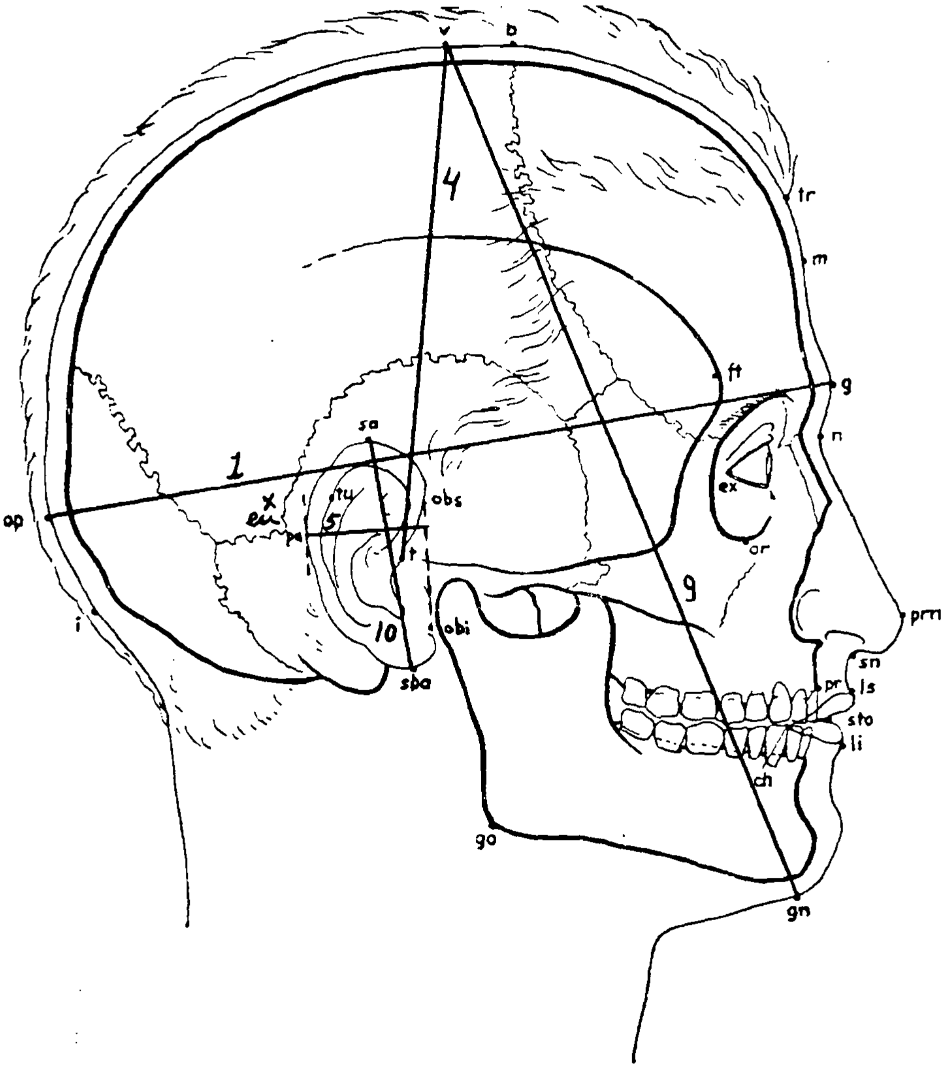
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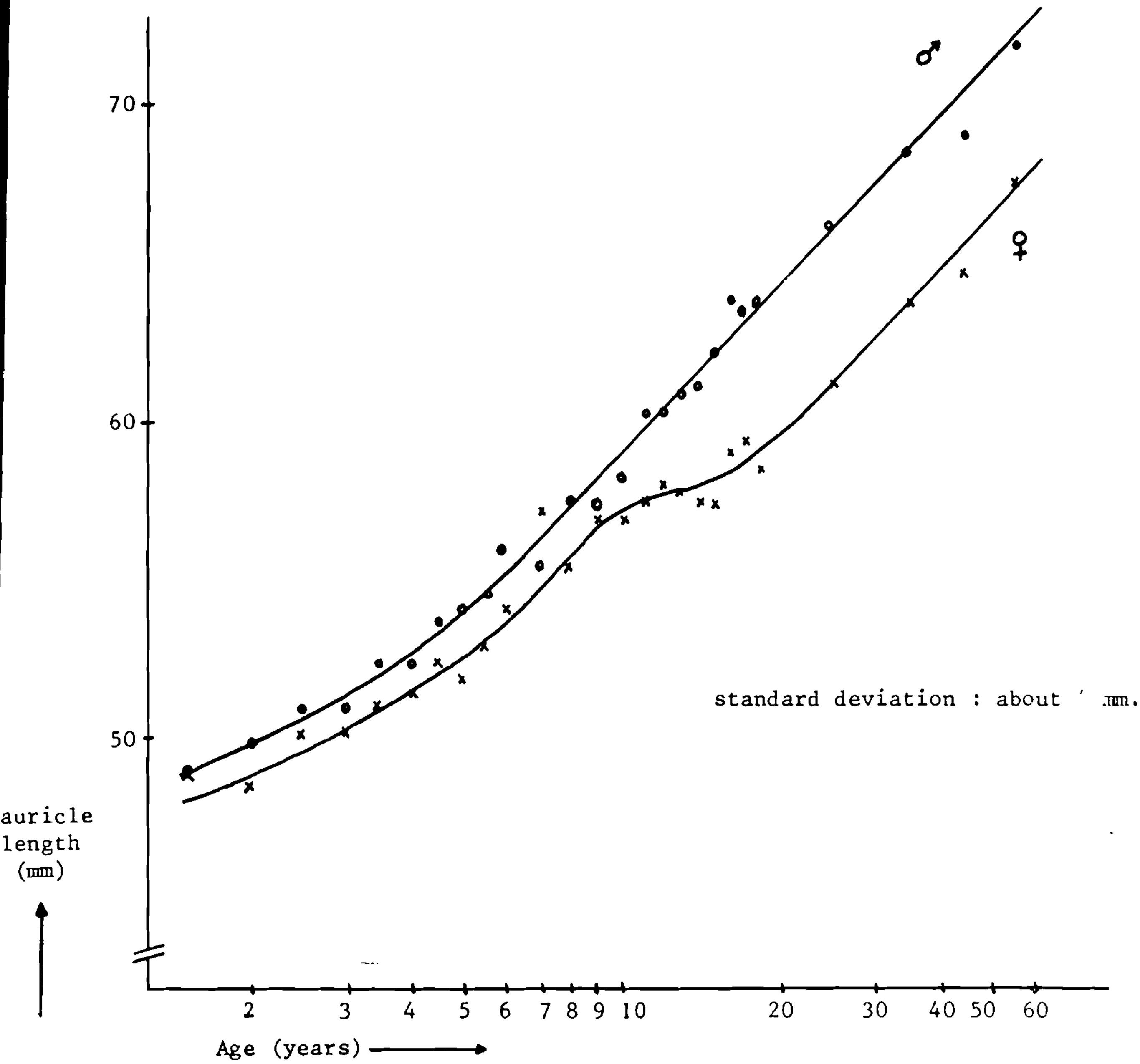

Fig.16. Auricle length as a function of age (Europeans).
Adapted from ref.33 and 34.

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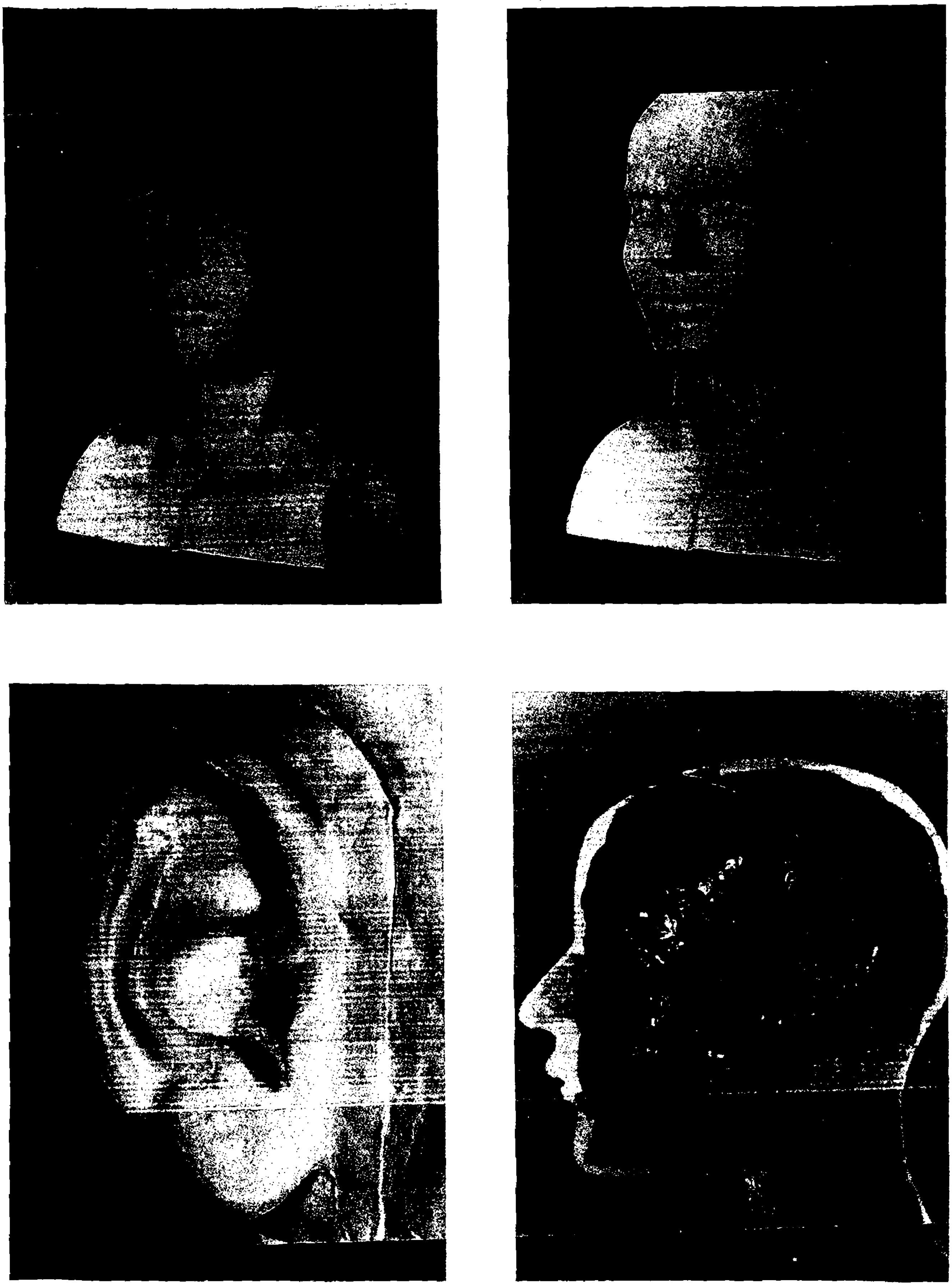
Acoustical impedance at the eardrum:
19, 21, 31, 32.



Photographs of the artificial head with and without a wig, and a view on the outer and inner sides of the active ear.