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ABSTRACT

Insertion gain and functional gain for two behind-the-ear hearing aids were measured on 17 subjects with sensorineural hearing loss. The results have been compared to the corresponding results for the two hearing aids measured on the occluded-ear simulator (IEC 711) and on a manikin (KEMAR).

The comparison shows that the frequency response of a hearing aid on the manikin differs only slightly from the mean of the insertion gain on the subjects. However, the range for the insertion gain on the subjects amounts to 20 dB at higher frequencies.

For each hearing aid the ratio between frequency response on occluded-ear simulator and insertion gain on the subjects simply corresponds to the transfer function from free field to eardrum.

This work was supported by the National Swedish Board for Technical Development and the Foundation of Tysta Skolan.

1. INTRODUCTION

It has been known for many years that the frequency responses of hearing aids measured on 2 cc coupler deviate substantially from the frequency responses on human ears. There are two explanations for this:

1) The 2 cc coupler was accepted as a standard in 1959 (IEC 126). It was intended to be a simple acoustical model of a closed human ear with earmould simulator. Sachs & Burkhard (1972) showed that the sound pressure level from the earphones can be up to 10-15 dB higher at the eardrum in a human ear than on the 2 cc coupler (Figure 1.1). Sachs & Burkhard explained that one reason for this difference is that the impedance of a human ear does not decrease as rapidly at higher frequencies as does the impedance of the 2 cc coupler.

IEC published, in 1981, a new standard, IEC 711, describing an occluded-ear simulator, which is an acoustical load closer to the impedance of an average human ear.

2) Several studies (e.g. Wiener & Ross 1946, Shaw 1974) have shown that the sound pressure level at the human eardrum is 15-20 dB higher compared to the free-field sound pressure level above 3 kHz. This effect must be considered when fitting a hearing aid using the frequency response measured under free-field conditions.

An attempt to solve this problem is to measure the hearing aid frequency response on a manikin. Burkhard & Sachs (1975) described such a manikin (KEMAR).

There may, however, be considerable differences between the hearing aid frequency responses on such a manikin and on human ears. There are great differences between the impedance data of different human ears, and the manikin represents an average subject. By measuring the sound pressure level in the auditory meatus of five subjects for several hearing aids Dalsgaard & Dyrlund Jensen (1976, Figure 1.2) showed great differences between the subjects.

The aim of the present investigation was to find out if the results of measurements of hearing aids on a manikin differ from the results on human ears, and if the differences are significant. Real ear gain (functional gain, Pascoe, 1975), was also measured and compared to the results of the described methods.

2. METHODS

The insertion gain of a hearing aid on a user is defined as the ratio of the eardrum sound pressure produced by the hearing aid in a sound field to the unaided eardrum sound pressure that would have been produced by the same sound field. See also Figure 2.1.

The functional gain is the the in-situ gain of a hearing aid, determined by the subjective threshold-difference method.

2.1 Subjects

In all, 17 hearing aid users, 6 males and 11 females, with sensorineural hearing loss participated voluntarily in this experiment. The age ranged from 20 to 65 (median 46). At the data treatment, one subject showed very diverging results. His results are shown separately, labelled subject No. 17.

Before the test with the hearing aids a clinical check-up was made, including a pure tone audiogram and tympanometry. An earmold impression was made from the subjects normally aided ear. If the subject used two hearing aids, the impression was made for the 'best ear'. The mean audiogram of the sixteen subjects as well as the audiogram of subject No. 17 are shown in Figure 2.2.

2.2 Equipment

2.2.1 Hearing aids

Two behind-the-ear hearing aids with top microphones, were used in the experiment. One was a broad band hearing aid (hearing aid A). The other one was a high tone hearing aid (hearing aid B). The microphone inlet on hearing aid A was placed above the receiver outlet tube, and below the receiver outlet tube on hearing aid B.

The gain controls of the two hearing aids were fixed in a medium setting, to ensure that the hearing aids worked in a linear mode. The settings were fixed in these positions during the whole experiment.

The free-field frequency responses for the two hearing aids are shown in Figure 2.3.

2.2.2 Earmoulds

The earmould impression made in the audiological clinic, was prepared for the test by cutting it to the same length as the subject's own personal earmould. Through the impression a hole was drilled for the tube. One single piece of tube was used from the hook of the hearing aid to the mouth of the impression. The tube was an ordinary hearing aid tubing with an inner diameter of 2 mm. The length of the tube was fitted individually for each subject. The mean length of the tubes for the seventeen subjects was 47 mm.

2.2.3 Probe tube microphone

Two types of microphone arrangements are commonly used for insertion gain measurements.

In one arrangement a miniature microphone is placed in the auditory meatus between the eardrum and the earmould. The microphone wires are led between the earmould and the wall of the auditory meatus (Wetzell & Harford, 1983).

The other arrangement consists of a thin silicon tube between the earmould and the wall of the auditory meatus, with its opening immediately in front of the eardrum. The microphone is connected to the tube and is thus kept outside the auditory meatus, (Pedersen 1982).

The documented knowledge about the influence of the probe microphone on the frequency response of a hearing aid is very limited. How much is the frequency response influenced by an extraneous object in the ear canal (the miniature microphone)? Is the frequency response influenced by the position of the microphone inlet in the auditory meatus? How much is the silicon tube flattened between the earmould and the wall of the auditory meatus. Does the silicone tube or the wires cause a leakage between the earmould and the wall?

In this study an another probe tube microphone was used, eliminating some of the possible drawbacks mentioned above. The probe tube microphone consists of a very narrow steel tube, connected by a rubber muff to a miniature microphone. The outer diameter of the tube was 1 mm and the length was 44 mm. The miniature microphone was a Knowles BT1751. The microphone as well as the rubber muff are available as spare parts for many behind-the-ear hearing aids. A microphone amplifier, was connected to the microphone. The frequency response of the probe tube microphone including the amplifier, is shown in Figure 2.4.

For the insertion gain measurements on the subjects, the steel tube was inserted through the earmould impression in parallel to the receiver outlet tube, ending 1-2 mm in front of the tip of the impression. After the subject had inserted the impression and the hearing aid, the miniature microphone was connected to the probe tube.

One advantage of this method is that the steel tube does not need to be cast in the earmould impression. Therefore the same steel tube can be used all the time. One disadvantage is that the steel tube requires a relatively straight auditory meatus. For that reason four persons, who volonteered to be subjects, had to be rejected.

2.2.4 Occluded-ear simulator

An occluded-ear simulator according to IEC 711 made by Bruel & Kjaer, type 4157, was used.

2.2.5 The manikin

The manikin used for this study was a KEMAR, which is a manikin with head and torso based on anthropometric data from more than 4000 American military male personnel. KEMAR is designed for hearing aid research measurements. An IEC-report (IEC 118-8: Methods of measurement of performance characteristics of hearing aids under simulated in situ working conditions) describes measurements that can be carried out on a manikin. The report also describes the physical measures for such a manikin. KEMAR fulfills these requirements. KEMAR was equipped with one neck ring, with large ear replica (DB 065) and with B&K occluded-ear simulator type 4157. No wig and no clothes were used. The ear canal simulator of KEMAR was manufactured from drawings by B&K.

The reference point of KEMAR (a point bisecting the line joining the centres of the ear simulator canals) was placed in the test point in the anechoic room.

2.2.6 Anechoic room

The experiment was carried out in an anechoic room with the dimensions 7.5m*4.2m*2.4m (L*W*H). The test point was choosen 1.5 m in front of the loudspeaker. The subject was seated in a chair with a neck support. The reference point of the subject (the same as for the manikin) was placed in the test point.

The loudspeaker consists of one loudspeaker element made by Technics with a honeycomb membrane in a closed box. The loudspeaker was placed on a stand with adjustable height. The front of the loudspeaker box was covered with a sound absorbing material to avoid reflections between the loudspeaker and the manikin/subjects.

2.2.7 Measuring equipment

To determine the functional gain, a Grason-Stadler Bekesy audiometer, connected to the loudspeaker via a power amplifier, was used. The maximum possible sound pressure level at the test point was 100 dB. The test signal was a pulsating pure tone.

The other measurements were performed with NASP, Network Analysis and Synthesis Package, which is developed at the department of Technical Audiology and installed on a minicomputer (Olofsson 1975, 1978). A broadband periodic test signal is presented via the D/A-converter of the computer and feeds the loudspeaker. The response from the hearing aid, via the probe tube microphone or the occluded-ear simulator, is returned to the computer via the A/D-converter. The computer compares the response of the hearing aid with the test signal. The result is presented on a graphical terminal and is stored in the computer for later analysis. The measurements were carried out in the frequency interval 200-7000 Hz. The sound pressure level of the test signal was 60 dB at the test point.

2.3 Measurements

The measurements on each subject consisted of two parts. In the first part the functional gain was determined for each hearing aid on the subject. In the second part the insertion gain was measured for the two hearing aids.

The hearing aids were measured in free-field and on the manikin, before and after the experiment, to check that their characteristics had not changed during the experiment.

2.3.1 Functional gain

The functional gain was determined by recording the hearing threshold for each subject with and without hearing aid in the frequency range 500-6000 Hz. It was not possible to determine the functional gain for six of the seventeen subjects. The maximum output from the loudspeaker, 100 dB SPL, was not enough to reach their hearing threshold without hearing aid in any part of the frequency range. Only four of the remaining eleven subjects had recordable hearing thresholds without hearing aid at the highest frequency.

2.3.2 Insertion gain

The sound pressure level in the auditory meatus was measured with the probe tube microphone, with and without hearing aids. Hearing aid A was measured first, and then hearing aid B. After that, hearing aid A was measured again for a check. The impression, on the other hand, was not removed from the subjects ear during all the measurements with the hearing aids.

2.3.3 Occluded-ear simulator

The measurements on the occluded-ear simulator were not carried out with an earmould simulator as standardized in IEC 711, because this earmould simulator cannot be used on the manikin. Instead the tube stud DP 0368 and a hearing aid tubing, 47 mm long, the mean length of the tubing of the subjects, was used.

In addition to the conventional measurements of the hearing aids on occluded-ear simulator, the sound pressure level in the cavity of the occluded-ear simulator was measured with the probe tube microphone. A narrow hole was drilled in the tube stud. The probe tube microphone was led 2 mm into the cavity of the occluded-ear simulator and the sound pressure levels from the hearing aids were measured. The reference plane between the tube stud and the cavity is defined to correspond to the position in the ear normally occupied by the tip of the earmould. Thus these measurements are similar to the corresponding measurements on the subjects with the hearing aids.

Figure 2.5 shows the ratio between the results for one hearing aid as measured with the B&K-microphone of the occluded-ear simulator with undrilled and drilled tube stud. Evidently the error introduced by the hole is negligible.

3. RESULTS AND DISCUSSION

In the following, the results of the sixteen subjects are presented first. The results of subject No. 17 are presented later in this section.

Comparing the insertion gain with the functional gain for the two hearing aids, Figure 3.1, we find a good agreement. However, it must be observed that the mean values for the functional gain represent only 5 subjects at 5 kHz and 3 subjects at 6 kHz.

Each middle curve in Figure 3.2 shows for one hearing aid the ratio between the mean insertion gain and the corresponding measurement on the manikin. The upper and lower curves show the 95% confidence interval for a t-test on the hypothesis that insertion gains on the subjects and on the manikin are equal. Since the ratio falls within the interval, there is no significant difference between the measurements. The ripple of the curves is due to the individual tube lengths, causing different resonance frequencies for the subjects.

Another interesting result is the ratio between the frequency response on the occluded-ear simulator and the mean insertion gain for the hearing aids, Figure 3.3. The result is in good agreement with the transfer function from free field to eardrum, Figure 3.4.

In this case no correction for the transfer function from free field to microphone inlet has been made.
Olsen & Carhart (1975) has pointed out that the diffraction is small for behind-the-ear hearing aids. This could be shown by the ratio between the measurements of the sound pressure levels in the auditory canals of the subjects and the sound pressure level in the occluded-ear simulator with probe tube microphone, Figure 3.5. Provided that the occluded-ear simulator correctly reproduces the acoustical impedance of the ear, the ratio simply represents the transfer function from free field to microphone inlet. My result is in good agreement with the observations of Olsen & Carhart.

A comparison between the curves for hearing aid A and B in Figures 3.2-3.5 shows that hearing aid B gives larger deviations from the expected values than hearing aid A. A possible explanation is the position of the microphone inlet on hearing aid B. If the tube of hearing aid B is too long, the aid slides down on the ear, thus making the external ear shadow the microphone inlet.

Figure 3.6 shows the individual insertion gains for the subjects. As can be seen the range amounts to 20 dB at higher frequencies.

The subjects were instructed not to move their heads. However, it is difficult to avoid small movements. Curves displaying the differences between the two measurements on hearing aid A for the 16 subjects are shown in Figure 3.7.

The result of subject No. 17 diverges from the other results, Figure 3.8. For him the insertion gain of each of the two hearing aids differed considerably from the mean insertion gain for the subjects. A closer examination at an audiological clinic revealed that he is a Valsalvablower and thus creates an overpressure in the middle ear. However, this fact can hardly explain the dips in the frequency curves.

4. CONCLUSIONS

The results of this investigation show no significant difference between the insertion gain measured on the manikin and on the average human ear for any of the two hearing aids. The investigation also reveals, that the ratio between the free-field frequency response of the hearing aids, and the insertion gain on human ears corresponds to the transfer function from free field to eardrum.

One conclusion from the discussion above is that it is not necessary to measure the frequency response of hearing aids on a manikin. Information for classification and for comparison of hearing aid performance can be gained from measurements on occluded-ear simulator under free field conditions combined with the known transfer function from free field to eardrum. Thereby the high accuracy of the free-field measurements can be maintained as far as possible. The use of a manikin just means an introduction of parameters difficult to control and therefore a severe risk of deteriorated accuracy.

To obtain the insertion gain for a behind-the-ear hearing aid, it is sufficient to compensate the free field frequency response measured on the occluded-ear simulator with the transfer function from free field to eardrum. For in-the-ear and body-worn hearing aids one must also compensate for their transfer functions from free field to microphone inlet.

As pointed out earlier, the variation between human ears is great. Accordingly great care must be observed at hearing aid fitting on patients. The average insertion gain, derived from free-field measurements as described above, or from a hearing aid data sheet, should thus be seen only as a guidance. To know the insertion gain for a hearing aid on a specific patient, as desirable in hearing aid fitting, measurements have to be performed on that very patient.

ACKNOWLEDGEMENT

I wish to express my gratitude to my colleagues for many valuable discussions and for their encouragement and criticism during the preparation of this report.
I am especially grateful to Ann-Cathrine Lindblad for her great help with the translation of this report.

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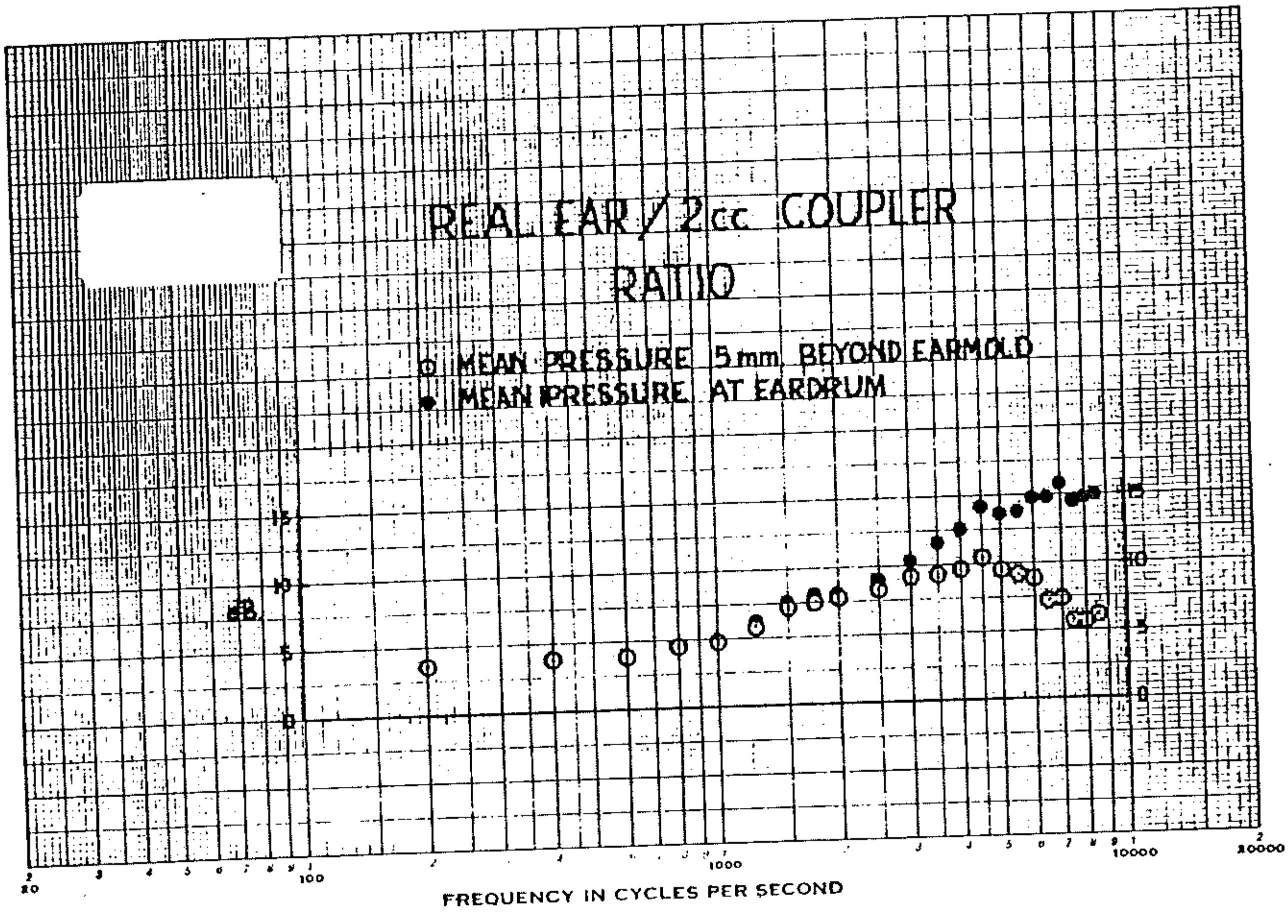
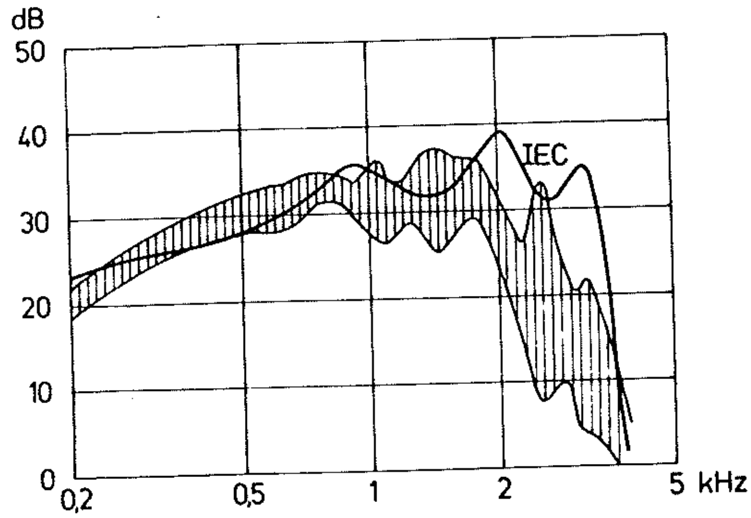
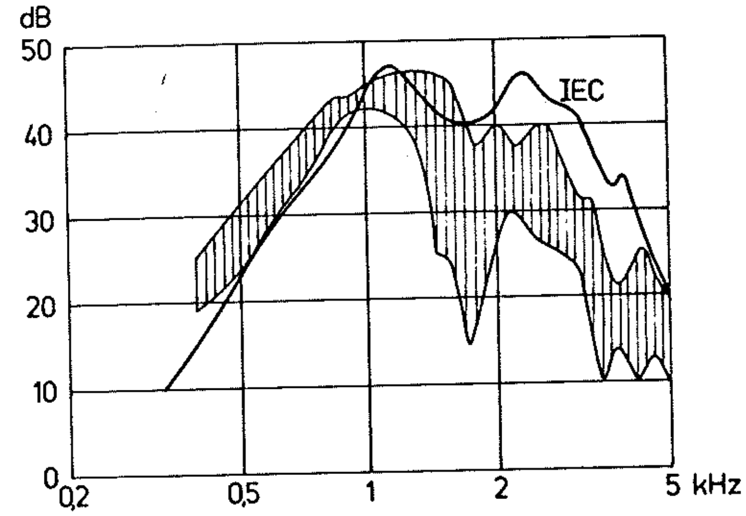


Fig. 1.1 Mean of real ear/2 cc coupler ratio for 11 subjects.
After Sachs & Burkhard (1972)



a) top microphone



b) bottom microphone

Fig. 1.2 Frequency response curves for two behind-the-ear hearing aids.
Shaded area: Range of insertion gain for 5 subjects.
Curve labelled IEC: Measured in accordance with IEC 118 and with 2 cc coupler (IEC 126).
After Dalsgaard & Dyrlund Jensen (1976).

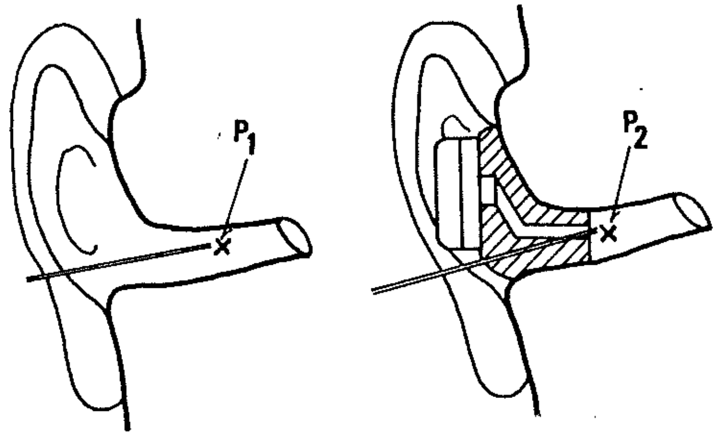


Fig. 2.1 The insertion gain is the ratio of sound pressures P_2 and P_1.
After Dalsgaard & Dyrlund Jensen (1976).

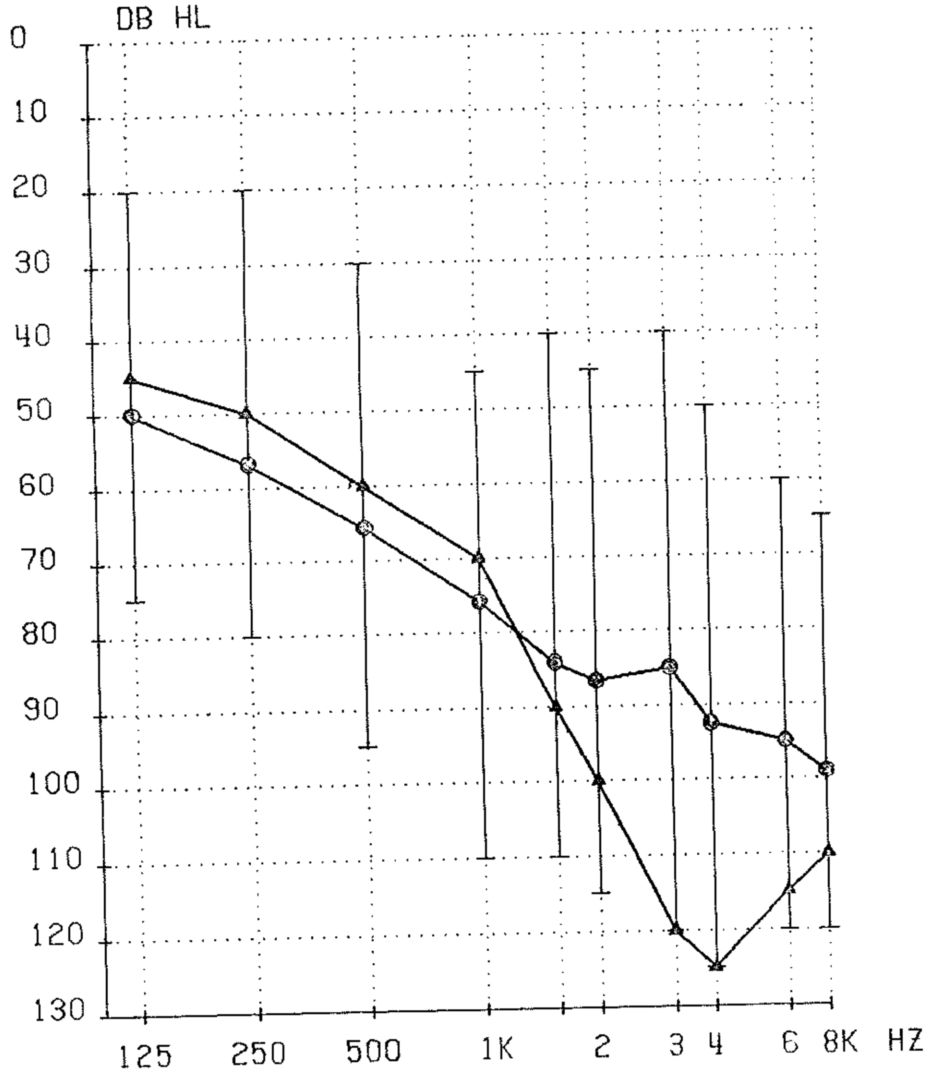
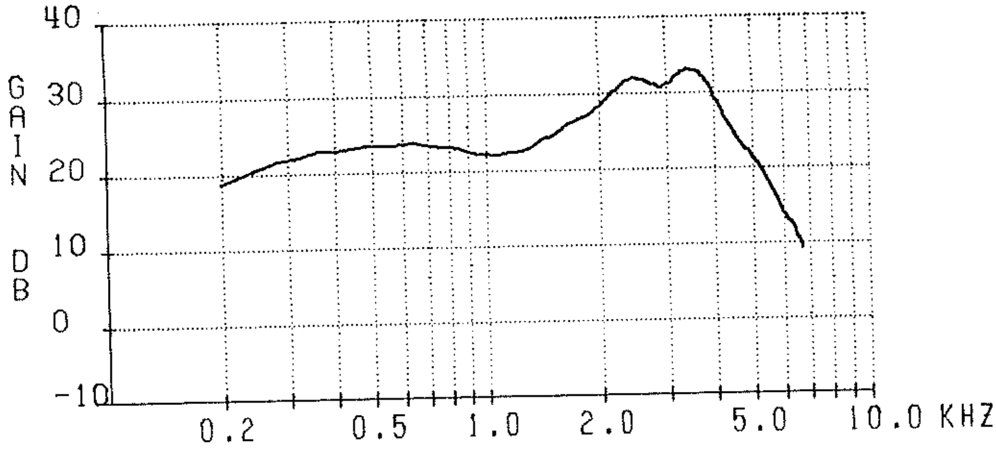
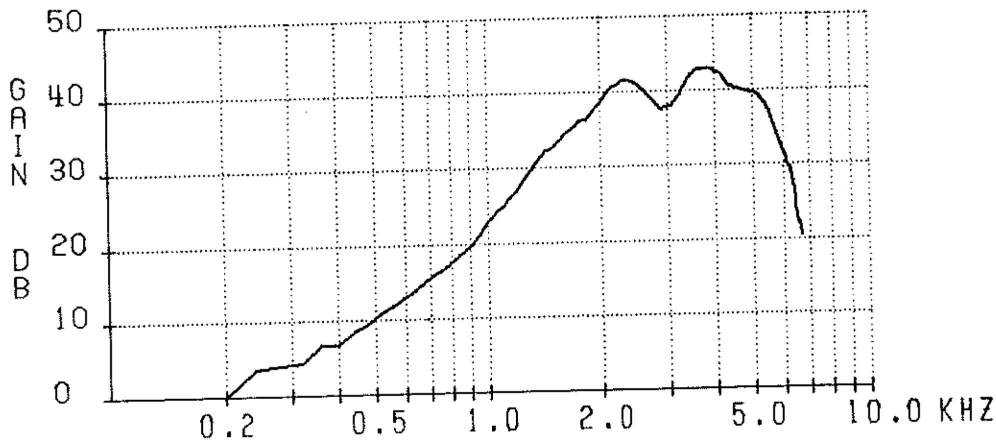


Fig. 2.2 Mean audiogram for 16 subjects - circles.
Audiogram for subject no. 17 - triangles.
Range of the audiograms - bars.



Hearing aid A



Hearing aid B

Fig. 2.3 Frequency responses of two hearing aids measured according to IEC 118-0 with occluded-ear simulator IEC 711.

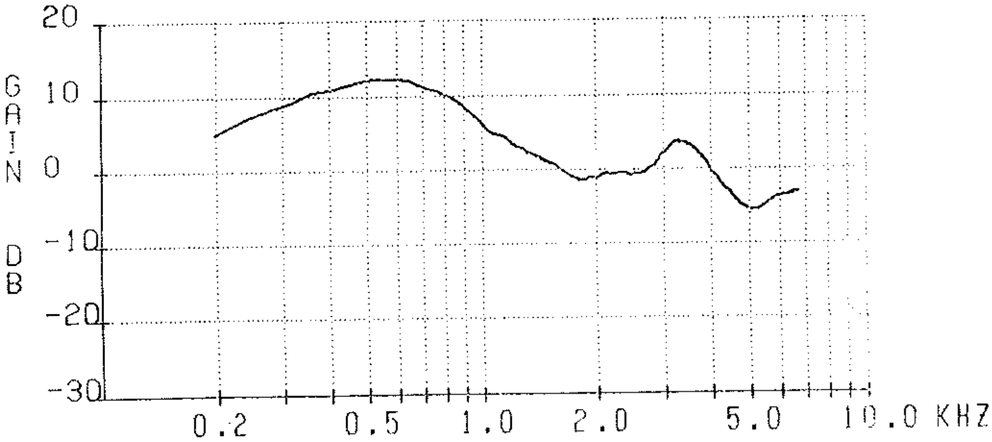


Fig. 2.4 Frequency response of probe tube microphone including microphone amplifier.

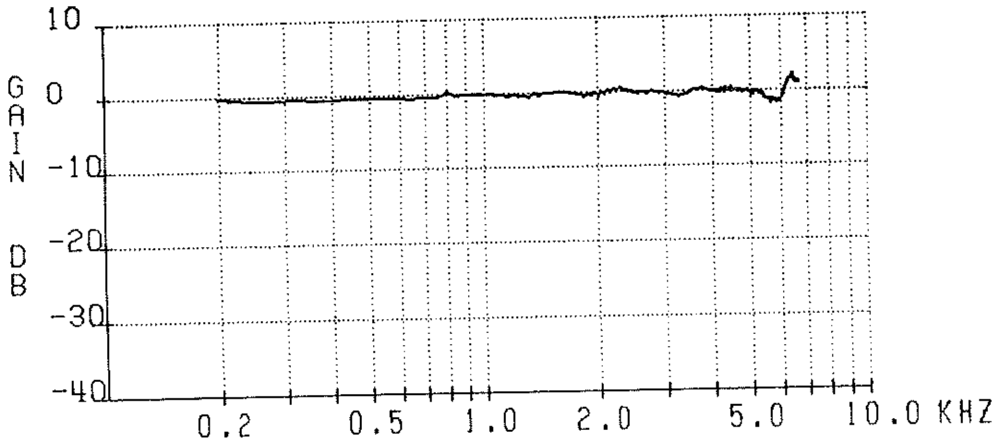
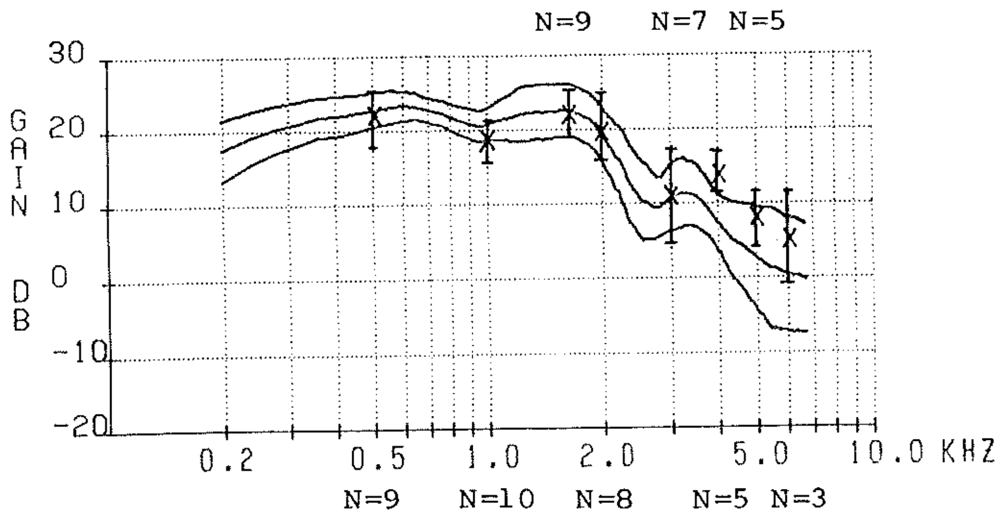
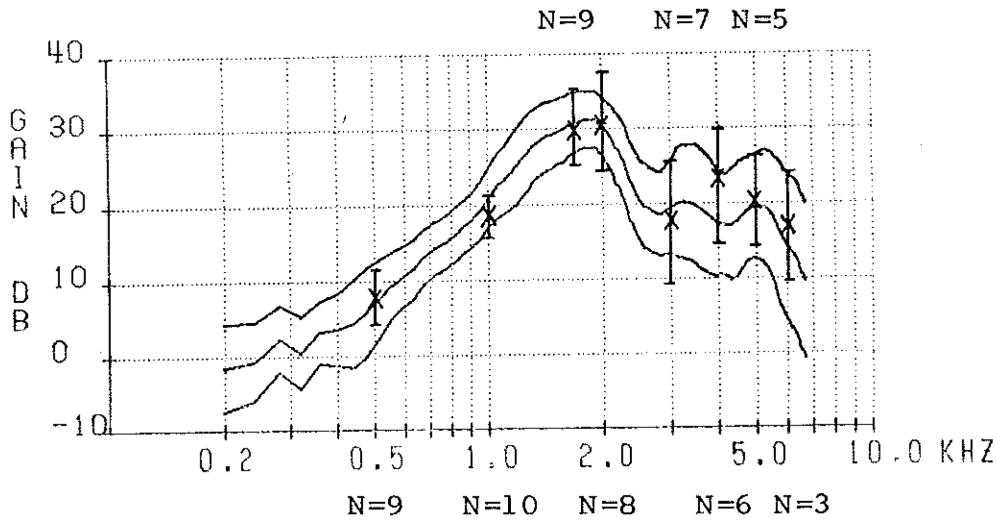


Fig. 2.5 Ratio between transfer functions of drilled and undrilled B&K tube stud. See text for explanations.

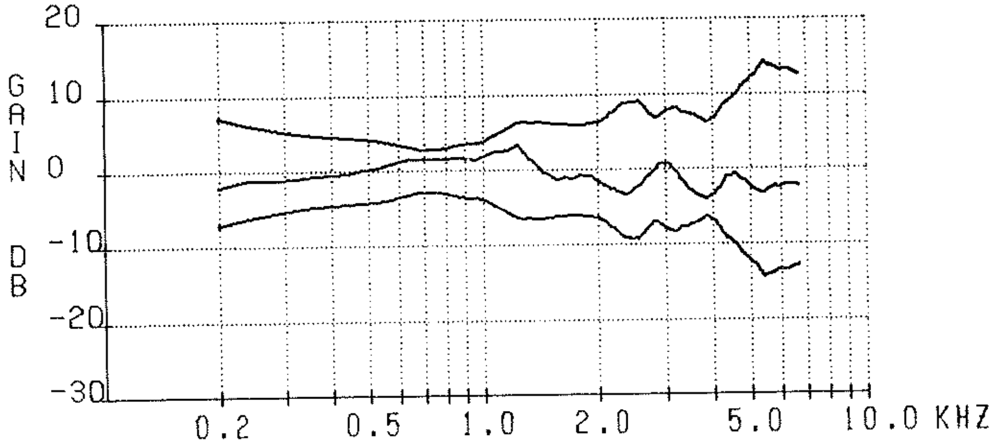


Hearing aid A

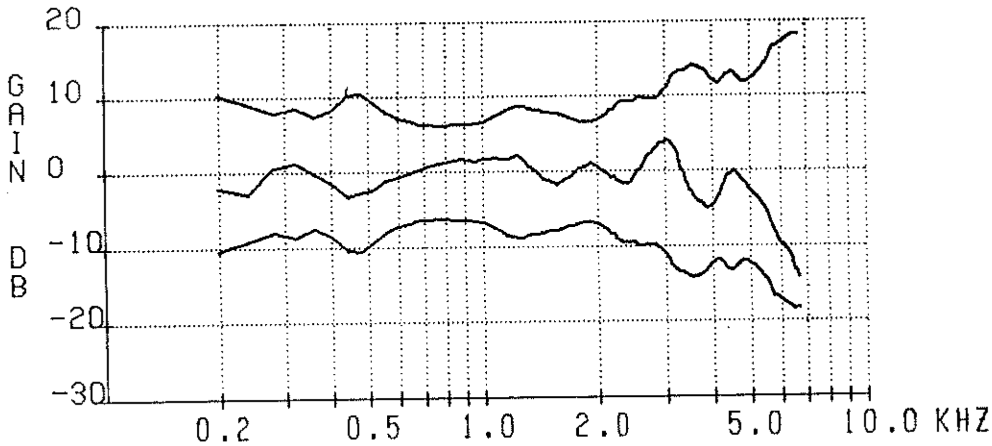


Hearing aid B

Fig. 3.1 Insertion gain of hearing aids A and B;
middle curve - mean
upper curve - mean + st. dev.
lower curve - mean - st. dev.
Mean and st. dev. of functional gain, crosses and bars.

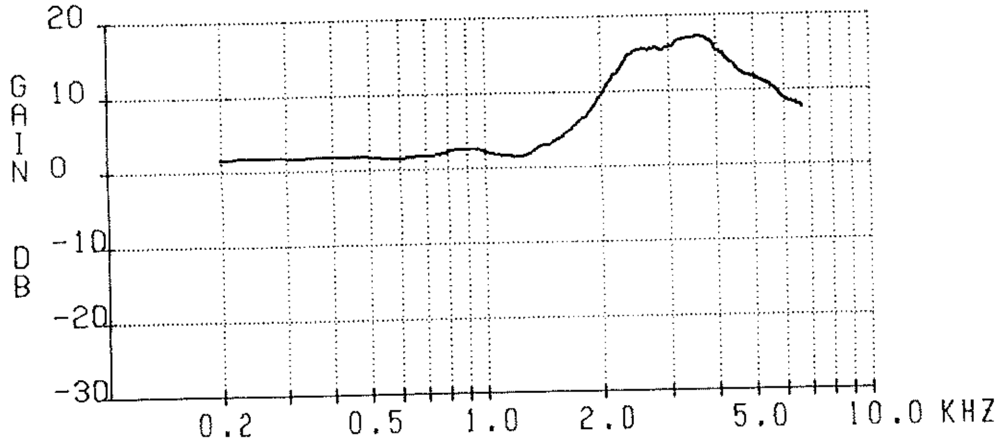


Hearing aid A

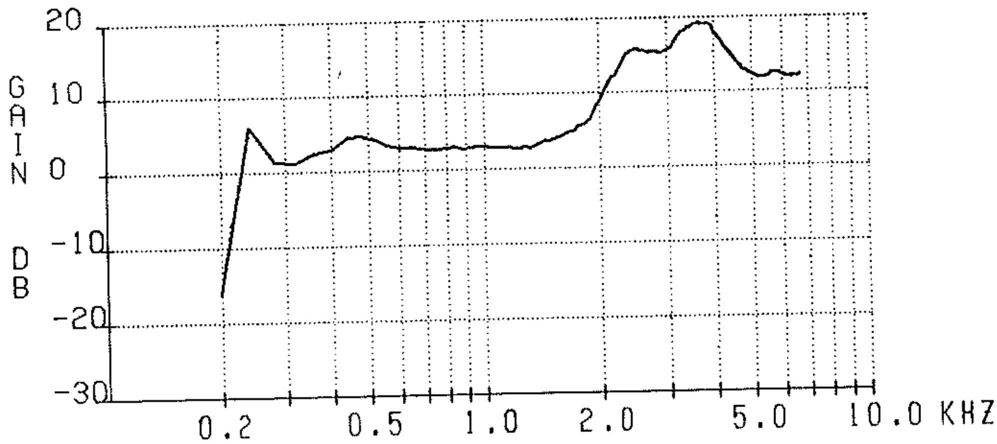


Hearing aid B

Fig. 3.2 Middle curve - ratio between mean insertion gain on subjects and on manikin.
Upper and lower curves - 95% confidence interval for a t-test on the hypothesis that insertion gain on subjects and on manikin are equal.

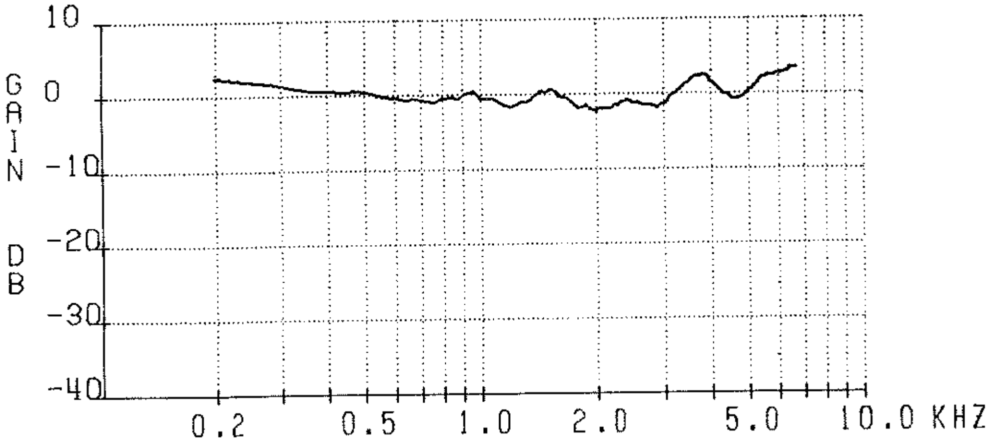


Hearing aid A

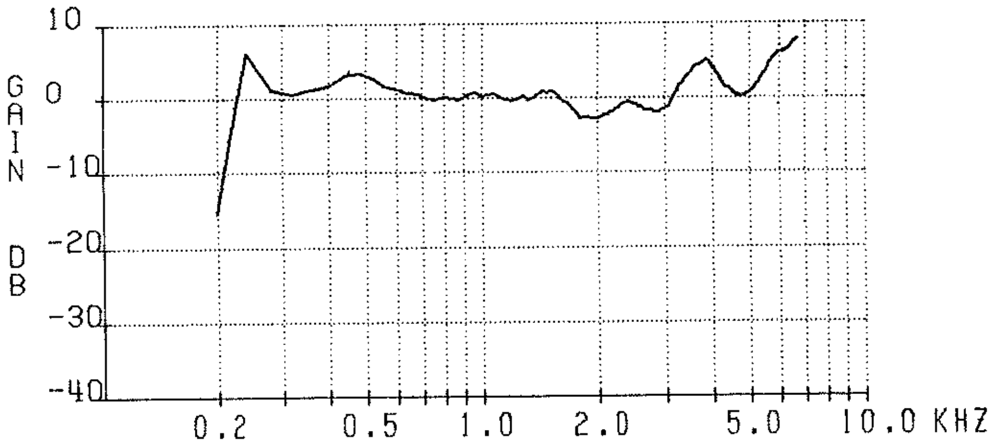


Hearing aid B

Fig. 3.3 Ratio between frequency response on occluded-ear simulator and mean insertion gain for 16 subjects for hearing aids A and B.

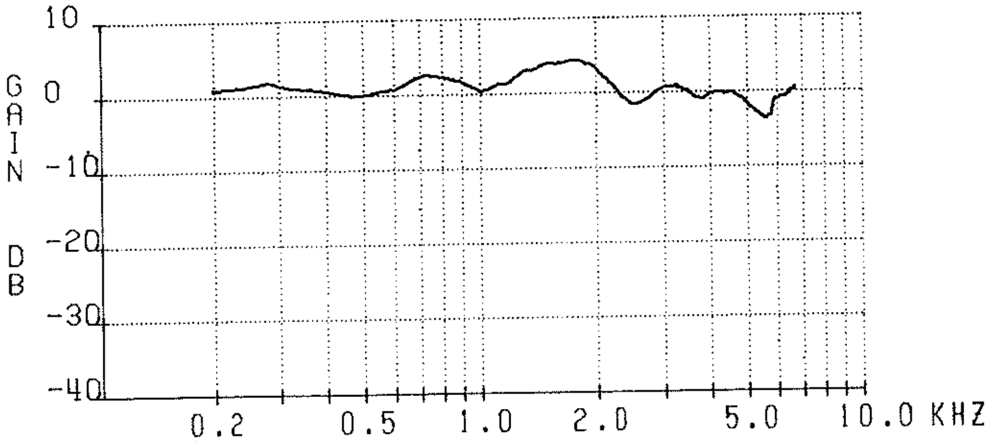


Hearing aid A

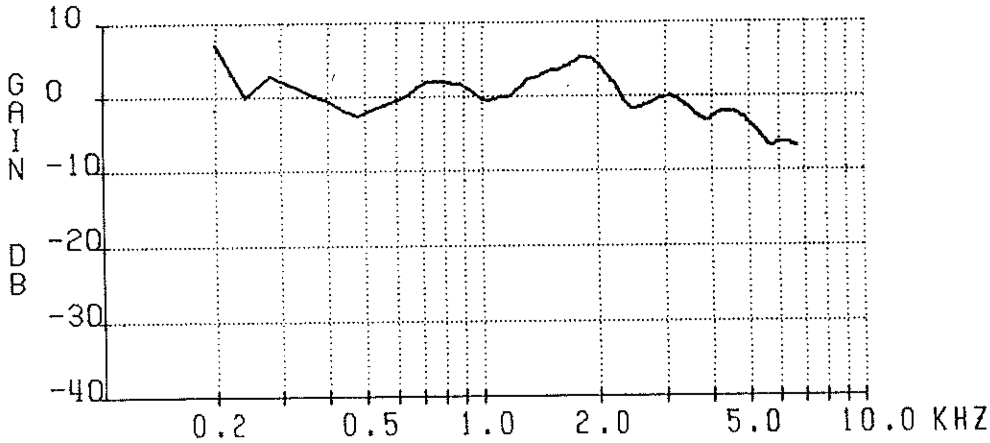


Hearing aid B

Fig. 3.4 Ratio between curves in Figure 3.3 and transfer function from free-field to eardrum, as measured on the manikin.

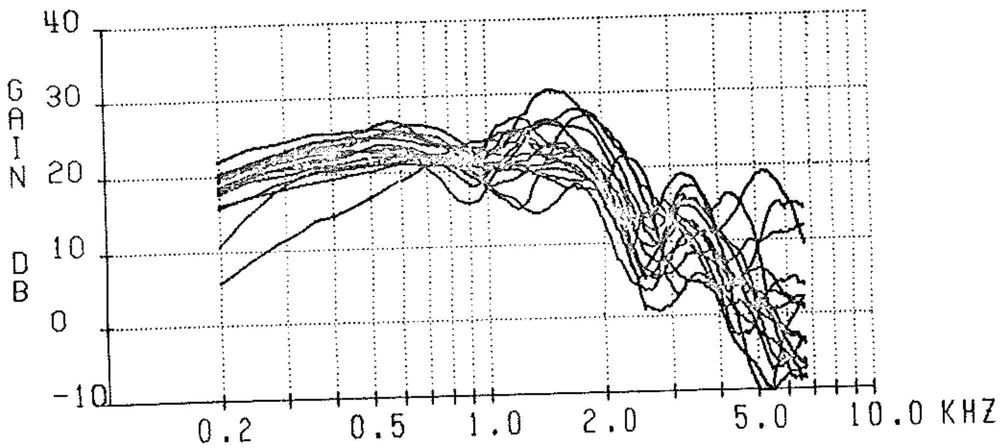


Hearing aid A

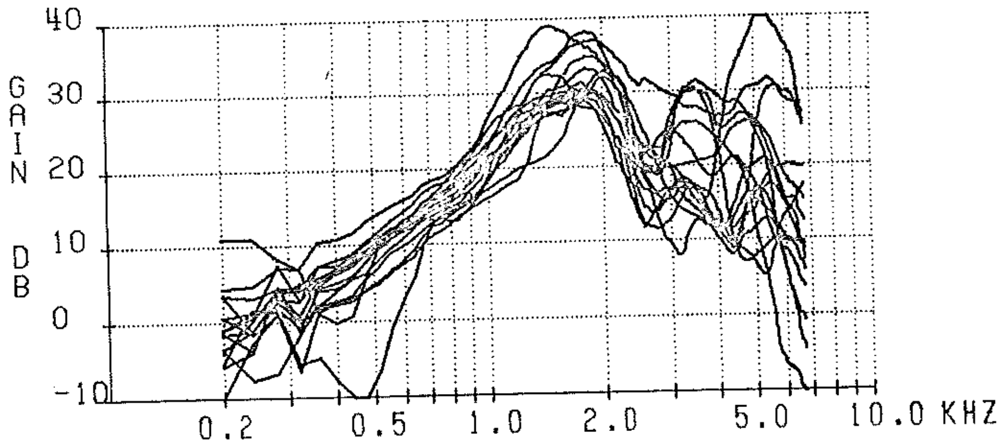


Hearing aid B

Fig. 3.5 Transfer function from free-field to microphone inlet.
See text for explanations.



Hearing aid A



Hearing aid B

Fig. 3.6 Insertion gain for the subjects on hearing aids A and B.

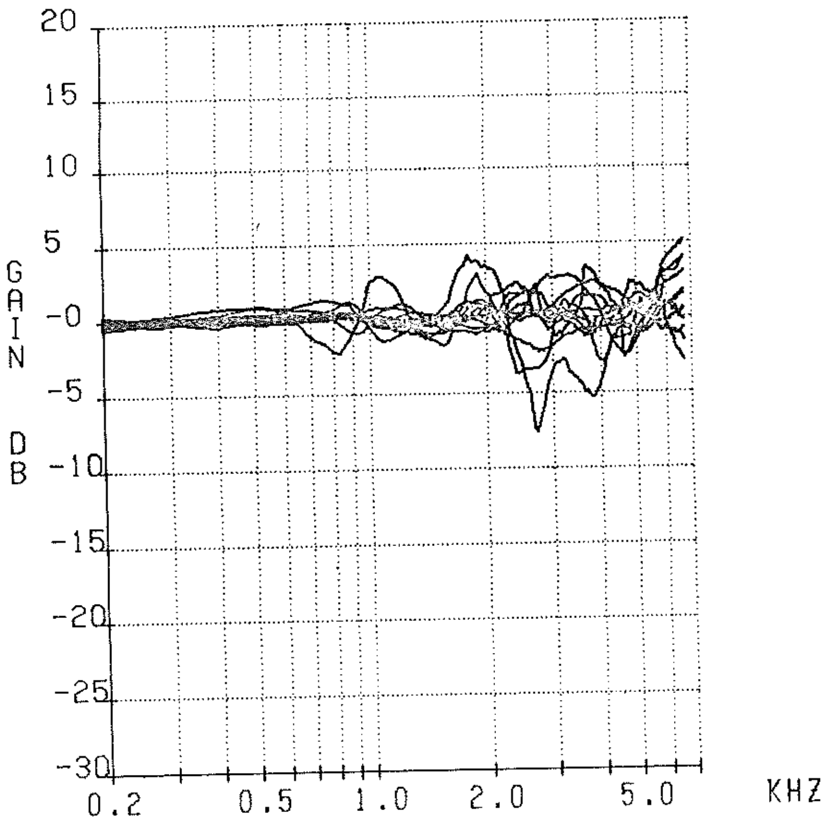
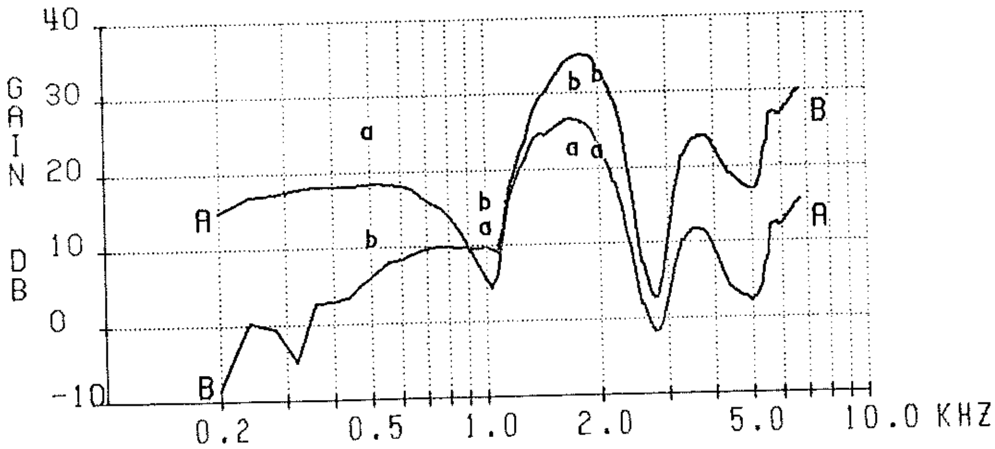
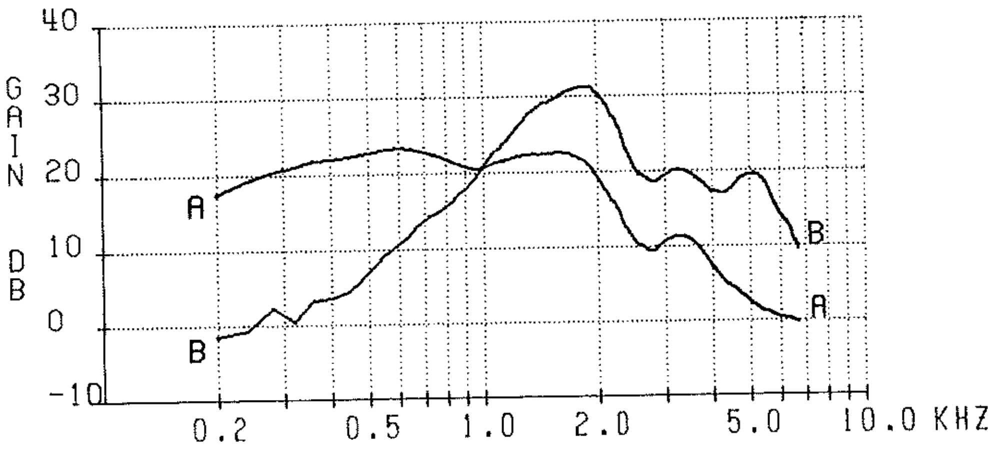


Fig. 3.7 Differences between the two measurements on hearing aid A for the 16 subjects.



Subject no. 17



Mean for 16 subjects

Fig. 3.8 Insertion gain for hearing aids A and B on subject no. 17.
'a' - functional gain for hearing aid A
'b' - functional gain for hearing aid B
Mean insertion gain for hearing aids A and B is shown for comparison.