ISSN 0280-6819

KAROLINSKA INSTITUTET

TECHNICAL AUDIOLOGY

Report TA130
Aug 1994

Ear muff performance in impulsive noise as a function of angle of incidence

Björn Hagerman, Åke Olofsson, Jun Cheng, Eva Svensson

KAROLINSKA INSTITUTET
TEKNISK AUDIOLOGI

1995-01-31

Error found in our report TA130

Unfortunately an error has beeen discovered in our report TA130, *Ear muff performance in impulsive noise as a function of angle of incidence*. It regards the A-filter curve used for calculating the L_C-L_A value of the impulses. Due to the presence of a DC-component at the recording, it would be necessary to use a very long impulse response of the filter at its convolution with the recorded impulse. This was not realized until now. Therefore, the filter curves actually obtained were not attenuating as much as they should at low frequencies.

We have now made new measurements (or rather new convolutions) to get correct L_C-L_A value of the impulses.

The error influences the PNR-values in Table II, page 8. **A revised page 8 is submitted.**

The new result shows that the PNR-values are good predictors for all impulses used, even for impulse No. 1 with its main energy around 100 Hz, as opposed to the statements in the discussion, conclusion and abstract of the report.

Yours sincerely

Björn Hagerman

Acknowledgment: The authors want to express their gratitude to Björn Jakobson, Peltor AB, who discovered the inconsistency of the result by reading the report very carefully.

Postadress:
Teknisk Audiologi
Box 70025
S-100 44 STOCKHOLM

Besöksadress:
Teknisk Audiologi
Lindstedtsvägen 7
Kungl Tekniska Högskolan
Stockholm

Telefon:
08-411 66 60
08-791 75 15
08-791 75 ..
08-791 75 19

Fax:
08-791 71 30

KAROLINSKA INSTITUTET
Teknisk Audiologi
Unit of Technical Audiology

ISSN 0280-6819
TA130, Aug 1994

Ear muff performance in impulsive noise as a function of angle of incidence

Björn Hagerman, Åke Olofsson, Jun Cheng, Eva Svensson

ABSTRACT

The European directives regarding noise exposure limits require knowledge of the attenuation of impulse noise obtained from hearing protectors. To clarify this matter a European joint project was performed. Our part of the project was to investigate the influence of sound incident angle on the attenuation of ear muffs, especially for impulse noises. The impulse response in the ear canal of 16 subjects was measured in an anechoic chamber at the incidence angles of 0° to +90° in steps of 15° and from 180°. This was made without ear muff and with three different types of ear muffs, Bilsom Viking 2421, Peltor H7A and Willson 358A, respectively. These impulse responses were then convolved with three types of impulses. Mean and standard deviation of attenuation values for the peak of the impulses were calculated (linear assumptions). In most cases the lowest attenuation of the peak was found at 180°. Attempts were made to predict these peak attenuation values from SNR (Single Number Rating), PNR (Predicted Noise level Reduction) and octave-band attenuation values proposed in ISO DIS 4869-2. The latter gave fairly good predictions in all cases, the PNR-values gave fairly good predictions except for the impulse with the main energy in the 125 Hz octave and the SNR-values gave good predictions only for the impulse with the main energy around 1 kHz. This investigation supports the idea to predict the attenuation for various types of impulse noises from attenuation data proposed in the ISO DIS 4869-2 standard, if the frequency region containing most energy is known.

This work was supported by the Swedish National Board for Industrial and Technical Development (NUTEK), grant No. 93-00276P.

Mailing address:
Teknisk Audiologi / KI
Box 70025
S-100 44 STOCKHOLM
Sweden

Visiting address:
Teknisk Audiologi
Lindstedtsvägen 7
Kgl. Tekniska Högskolan
Stockholm

Telephone:
Nat.: 08-411 66 60
Int.: +46 8 411 66 60

Fax:
Nat.: 08-791 71 30
Int.: +46 8 791 71 30

ISSN 0280-6819
TA130, Aug 1994

CONTENTS Page

ISSN 0280-6819
TA130, Aug 1994

INTRODUCTION

In the European Council directive (86/188/EEC) on the protection of workers from the risk related to exposure to noise at work 200 Pa (140 dB SPL) has been chosen as an exposure limit for instantaneous sound pressure levels. The European Council directive (89/686/EEC) states that all hearing protectors must bear labelling indicating noise attenuation level. At present, there is no standardised method to determine the peak sound pressure level at the eardrum when hearing protectors are used, to form a basis for calculating the attenuation of the peak values of the impulses. Even when the system is linear, it is impossible to estimate the peak level of impulses because the ISO 4869-1 threshold method provides attenuation figures only; the phase relations, also required to calculate the impulse response, are unknown. Thus, at present there is no procedure to inspect whether occupational noise exposure exceeds the limits in the above mentioned European directive.

To solve this problem a research program was set up within the third program of the EC Bureau Communautaire de Référence, 1993-1994. Nine European laboratories are involved. TNO Institute of perception, Soesterberg, Holland is the coordinator.

Our contribution was to investigate the influence of sound incident angle on the attenuation of ear muffs, especially for impulse noises. In addition, attenuation values in a diffuse sound field according to ISO 4869-1 and corresponding values by a probe microphone technique was measured on the same group of subjects. The result of this second part of the investigation is reported elsewhere (Hagerman et al., 1994).

The purpose of the experiment reported on here was to investigate the influence of sound incident angle on the attenuation of ear muffs, especially for impulse noises at moderate levels where no nonlinearities are expected.

METHODS

Equipment

The measurements were performed in an anechoic chamber (Till & Hagerman, 1991). The subject was seated in a rotatable chair with armrests. The reference point, in the middle of the head between the two ears, was situated 2.13 m in front of the loudspeaker (Fane, Studio 8M, Ø 8 1/4"). In order to get the specified angle of incidence the subject wore an adjustable headband with a stiff wire pointing forwards. Twentythree cm in front of the head it ended with a small loop (Ø 6 mm). Through this loop the subject could aim with one eye at the mark on the wall indicating the actual angle of incidence.

A periodic chirp was used as the test signal, produced by the hardware equipment TAMP3 developed at our laboratory. The period time was 16.7 ms (60 Hz periodicity) and 100 periods were used for each measurement giving a measurement time of 1.67 s. The measurements were performed from 120 to 9000 Hz. For the analysis the same equipment was used together with the software program NAP (Network Analysis Program) also developed at our laboratory. The level of the chirp signal at the reference point was approximately 75 dB SPL for measurements without a hearing protector and 10 dB higher, i.e. approximately 85 dB SPL, for measurements with a hearing protector. In the pilot tests it was checked that the noise from the microphone did not influence the measurement results.

The sound pressure level in the ear canal was measured according to the MIRE-method (Microphone In Real Ear) developed at TNO, Soesterberg, Holland. The microphone type was Sennheiser KE-211-9 equipped with a probe tube 12.5 mm of length. The inner diameter was 1 mm and the outer diameter was 2.2 mm. It was mounted on a wire arrangement used to support the microphone at the entrance of the ear canal (Smoorenburg et al., 1993). The whole assembly was bought from TNO. The preamplifier was built in our laboratory, according to a design from TNO.

Hearing protectors

Three earmuffs were tested, Bilsom Viking 2421, Peltor H7A and Willson 358A. One sample of each type was used. They were not conditioned before the test.

Subjects

Sixteen subjects participated, 15 males and 1 female. Their mean age was 27 years. They were tested for normal hearing. All of them had hearing thresholds better than 15 dB HL between 125 and 2000 Hz and better than 25 dB HL between 3000 and 8000 Hz.

Procedure

The right ear of the test subject was checked by otoscopy before the probe was mounted. The experimenter put on the hearing protector. All measurements were performed with the probe microphone in the subject's right ear, and only directions with the sound source at the right side of the head were tested. The directions were tested in the following order:

0°, 15°, 30°, 45°, 60°, 75°, 90°, 180°, 0°.

Please note that a retest was made at the end with the loudspeaker in front of the subject.

The subject was informed by the experimenter through the loudspeaker about the actual direction. The subject confirmed when he was ready. Then the measurement was performed.

The order of protector type was permuted among the subjects, but was the same as for the measurements in the sound proof booth reported by Hagerman et al. (1994). About half of the subjects started with the measurement in the sound proof booth and then went directly to the measurements in the anechoic chamber. The other subjects were measured in the opposite order. The probe microphone remained in the ear canal during the whole session.

Impulse noises

For calculation of peak attenuation four impulse noises were considered, one of each of the four types described by Wheeler (1992). Four recordings, one of each type, were obtained from Wheeler's research group on a DAT-tape. They were recorded with the sampling frequency used for the measurements and stored in the computer. The spectra and pressure vs. time waveforms are shown in Figure 1a-d. However, it was noted later, that the peak levels of impulse No. 3, detonation of 64 kg of plastic explosive at 500 m, could not be correctly calculated by our convolution program since the main energy was located at very low frequencies. For theoretical reasons the directional dependence should also be negligible in this frequency region (≈10 Hz). Therefore, the impulse No. 3 was not used.

Calculations

Frequency dependent attenuation curves for the hearing protectors were obtained as the quotient of the transfer functions from the electrical signal into the loudspeaker to the output from the probe microphone with and without hearing protectors. The impulse responses were calculated as inverse Fourier transforms of the complex attenuation values. Means and standard deviations of frequency curves were calculated using the amplitude curves in dB. Peak values in the ear canal were calculated by taking the maximum absolute value of the sequence obtained by convolution of the impulse responses of the ear protectors at the ear with the impulses from the DAT-tape. Peak attenuation values were calculated as the difference between the peak of the absolute value (in dB) without hearing protector and the corresponding value with hearing protector. Statistical analyses were performed with the computer program STATGRAPHICS®.

RESULTS AND DISCUSSION

Open ear responses

The mean open ear frequency responses with angle of incidence as parameter are shown in Figure 2. The curves are smoothed with a gliding one-third-octave-band digital filter. The 180°-curve is easily distinguished from the other being the lowest one between 2 and 5 kHz. At 6 kHz the others are ordered from 90° to 15° from above downwards. The two lowest curves at 6 kHz are test and retest at 0°.

These curves can be compared with that of Hellström (1993) with the probe tip close to the eardrum. There are two main differences between our results. One is the frequency of the resonance peak, which is at 2 kHz in our results and 2.5 kHz in Hellström's. The second is the level in the 3 to 6 kHz region which is 4 to 7 dB lower in our results. Compared to the results of Shaw and Vaillancourt (1985) similar but 1 to 3 dB larger differences were obtained. The most important reason for these differences is the position of the probe tip (Hagerman et al., 1994). This is in good agreement with the result of Hellström (1993) for various placements of the probe tip in the ear canal. Our placement would be expected to give a mean distance from the ear drum of about 14 mm.

Attenuation curves for various directions

Figures 3a-c show the mean attenuation over subjects for each type of muff measured with the MIRE method as a function of frequency with angle of incidence as a parameter. The curves are smoothed with a gliding one-third-octave-band digital filter. For each type of muff the curve showing the lowest attenuation at 1 kHz is the one for 180°. Since testing in diffuse field according to ISO 4869-1 gives sound from all directions, such measurements probably give attenuation values similar to that of the worst direction in the free field for each frequency. This matter is illuminated in the report by Hagerman et al. (1994).

Repeatability

The peak attenuation is calculated for each direction as the difference between the result without the ear muff and the result with the ear muff. Therefore it is important that the head is turned in the same direction for both these measurements. The error introduced by a discrepancy in this respect was assessed in the following way: After the measurement at 180° the subject turned back to 0° and the measurement at 0° was repeated. The mean and the standard deviation of the differences between the corresponding two peak values of the impulse were calculated (N=48, 16 subjects times 3 impulses) for the case without protector and for the three protectors respectively. To get the standard deviation for repeated measurements these standard deviations were divided by $\sqrt{2}$, see Table I.

Table I. Mean difference between retest and test at 0° and calculated standard deviations (dB) of peak sound pressure levels in the ear canal for repeated measurements.

	Mean diff.	**SD**
Open ear	0.01	0.37
Bilsom Viking 2421	-0.37	0.34
Peltor H7A	-0.38	0.42
Willson 358A	-0.98	0.64

The negative mean values indicate that the attenuation increase slightly over time, since a corresponding change is not seen for the open ear. The repeatability looks very good. However, for the repeatability of the attenuation, the figures concerning the open ear and the actual protector have to be considered together. Their variances should be added. This gives a standard deviation of 0.74 dB for repeated measurements of peak attenuation at 0° at the worst case (Willson 358A). That result is considered to be quite acceptable.

Peak levels in the ear canal

Figures 4a-d show the calculated relative peak levels in the ear canal as a function of angle of incidence and with type of impulse as a parameter. The maximum value for each curve is arbitrarily set to 0 dB. The peak level without protector is shown in Figure 4a and the peak levels under the various protectors are shown in Figures 4b-d respectively.

Note that the maximum value is obtained at 60° in the open ear but mostly at 90° under the ear muffs for all types of impulses.

Peak attenuation

The most interesting result according to the purpose of the investigation is the peak attenuation, i.e the difference between the highest peak value without muff and the highest peak value with muff. This is shown for the various muffs and impulses in Figure 5a-d (mean values over 16 subjects) and in Figure 6a-c (**mean - SD** over 16 subjects). The lowest peak attenuation is found at 180°. The reason is of course that the peak level is already rather low at 180° without protector, together with the fact that the directional dependence with protector is somewhat smaller than without protector.

Is it possible to predict the peak attenuation from the ordinary data of the hearing protector and from some information about the type of impulse? According to ISO DIS 4869-2 data from the hearing protector may include the SNR_x-value (Single Number Rating), the H_x, M_x and L_x-values and attenuation values for each octave frequency 125-8000 Hz. The H, M and L values indicate the attenuation at high, medium and low frequencies respectively and the index $_x$ denotes protection performance in %, i.e. the percentage of subjects expected to obtain at least the indicated attenuation value for high, medium and low frequencies respectively. These may be used to calculate a predicted noise level reduction (PNR_x) for a given type of noise. The difference between the C- and the A-weighted sound pressure levels of the actual noise is required for this calculation. In Figure 1 the frequency region containing most energy can be found for each impulse and in Table II below the attenuation at the corresponding octave frequency is included. Here the actual peak attenuation can be compared to these various predicted attenuation values.

ISSN 0280-6819
TA130, Aug 1994

Table II. Actual calculated peak attenuation in dB (**mean - SD**) for the various protectors and impulses at the angle of lowest attenuation compared to proposed standardized attenuation indices SNR and PNR calculated from results according to ISO 4869-1 and ISO DIS 4869-2 on the same subject group and protector samples. The values at the octave frequencies are mean - SD real ear attenuation at threshold (REAT). (Please note that the index $_{85}$ denotes the protection performance in percentage and has nothing to do with the exposure limit 85 dB for continuous noise.)

Impulse No. 1 - 20 tonne drop forge at 20 m, $L_C - L_A = 15.3$ dB

	SNR_{85}	PNR_{85}	125 Hz	**Actual**
Bilsom Viking	27	9.0	8.0	**7.5**
Peltor H7A	28	9.4	8.4	**6.9**
Willson 358A	24	6.0	4.8	**2.9**

Impulse No. 2 - Impact welder at 1.5 m, $L_C - L_A = -0.1$ dB

	SNR_{85}	PNR_{85}	4 kHz	**Actual**
Bilsom Viking	27	28.7	38.9	**30.1**
Peltor H7A	28	30.2	31.9	**28.4**
Willson 358A	24	25.7	31.6	**25.2**

Impulse No. 4 - Pistol at 1 m, $L_C - L_A = 0.4$ dB

	SNR_{85}	PNR_{85}	500 Hz	1 kHz	**Actual**
Bilsom Viking	27	27.6	27.4	28.2	**28.5**
Peltor H7A	28	29.2	27.3	32.0	**29.9**
Willson 358A	24	24.6	20.8	29.5	**25.9**

The PNR-values are based on the HML-values according to Table III below.

Table III. SNR, H, M, and L-values (dB) of the three ear muffs according to ISO 4869-1 and ISO DIS 4869-2, calculated from subjective results as reported in Hagerman et al. (1994).

	SNR_{85}	H_{85}	M_{85}	L_{85}
Bilsom Viking	27	33	24	15
Peltor H7A	28	34	26	16
Willson 358A	24	30	21	12

For impulse No. 1 with most energy in the 125 Hz octave only the attenuation values at the corresponding octave are good predictors of impulse attenuation. The PNR-values give predictions about 10 dB too high and the SNR-values are about 20 dB too high.

For impulse No. 2, however, with the energy concentrated to the 4 kHz region, our probe measurements gave 7 dB too low values according to Hagerman et al. (1994). This was probably caused by the probe placement used in the present investigation and not due to bad predictors. Considering that, the octave-band-values as well as the the PNR-values are fairly good predictors. The SNR-values give 7-10 dB too low predictions.

Finally, for impulse No. 4 with the main energy in the middle frequency range all predictors are good.

CONCLUSIONS

The best predictor of the peak attenuation of a hearing protector is attenuation at that octave frequency where the most energy of the impulse is found. The PNR-value, based on HML-values, is rather good except for impulses with energy at low frequencies. The SNR-value is a good predictor only for impulses with the main energy in the middle frequency area.

Measurement results in the region 4-8 kHz have to be interpreted with caution due to possible errors caused by the probe placement used in this investigation (see Hagerman, 1994).

On the whole, this investigation supports the idea to predict the attenuation for various types of impulse noises from attenuation data calculated according to the ISO DIS 4869-2 draft standard, if the frequency region containing most energy is known.

ACKNOWLEDGMENTS

The authors wish to thank the participants in the European consortium cooperating in the whole project and among them especially the convener prof. Guido Smoorenburg and also David Smeatham for providing recordings of the impulse noises.

This work was supported by the Swedish National Board for Industrial and Technical Development (NUTEK), grant No. 93-00276P.

REFERENCES

Hagerman B, Olofsson Å, Cheng J, Svensson E. 1994. Ear muff performance determined by threshold method and by probe microphone method. Technical Audiology Reports No. 131, Karolinska institutet, Stockholm.

Hellström P-A. 1993. Miniature microphone probe tube measurements in the external auditory canal. *J Acoust Soc Am 93(2)*, 907-919.

ISO 4869-1: 1990, International Organisation for Standardization, Acoustics - Hearing protectors - Part 1: Subjective method for the measurement of sound attenuation.

ISO DIS 4869-2, International Organisation for Standardization, Acoustics - Hearing protectors - Part 2: Estimation of effective A-weighted sound pressure levels when hearing protectors are worn.

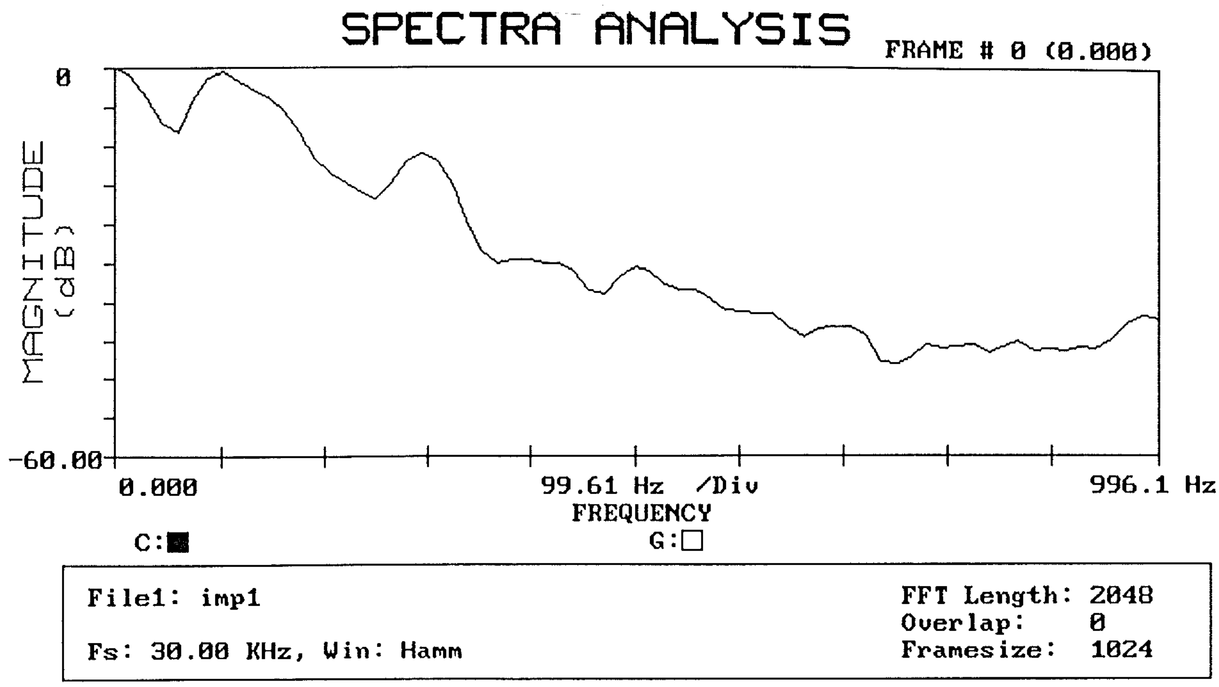
Shaw EAG, Vaillancourt MM. 1985. Transformation of sound-pressure level from the free field to the eardrum presented in numerical form. *J Acoust Soc Am 78(3)*, 1120-1123.

Smoorenburg GF, Bronkhorst AW, Soede W & de Reus AJC. 1993. Assessment of hearing protector performance in impulse noise; feasability study part II: Methods. TNO Report IZF 1993 C-32, TNO Defence Research, Soesterberg, The Netherlands.

Till O, Hagerman B. 1991. A renovated anechoic room: Some aspects of requirements and measurements. Technical Audiology Reports No. 121, Karolinska Institute, Stockholm

Wheeler PH. 1992. Hearing protector performance in impulsive noise (feasability study on impulsive noise sources). Report No: SAL/HP/92/01. Department of applied acoustics, University of Salford, England.

FIGURES



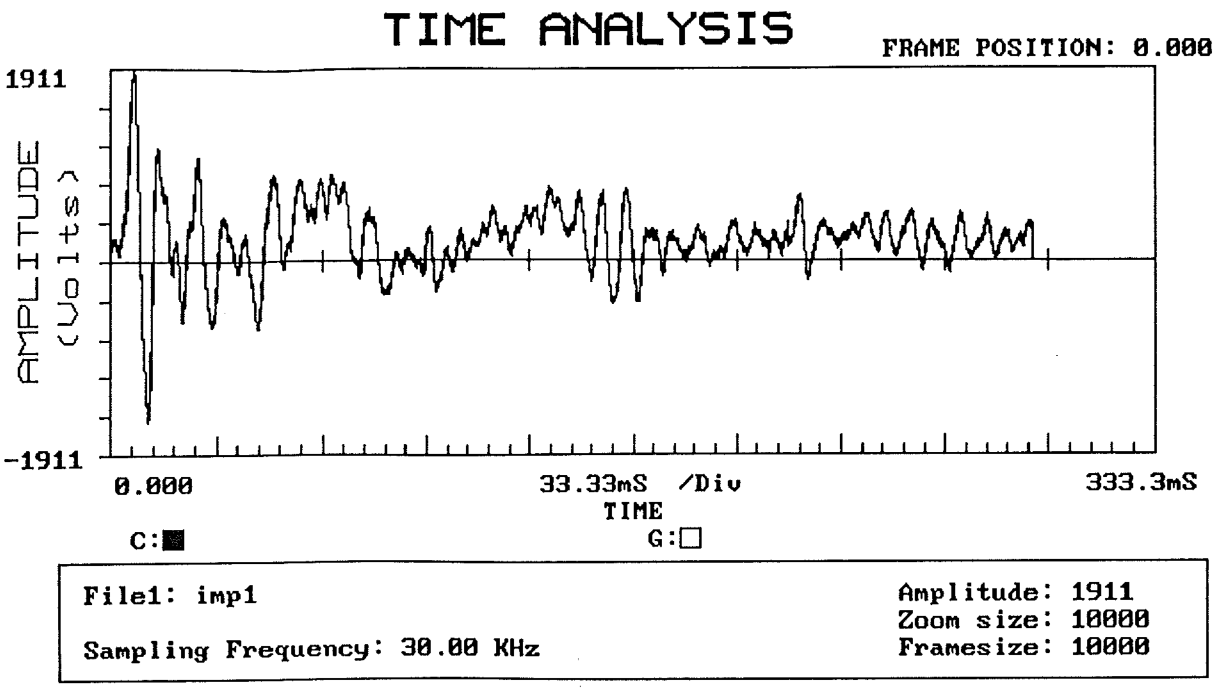


Figure 1a. Power spectrum and pressure-time waveform for impulse No. 1, 20 tonne drop forge at 3 m, with long B-duration.

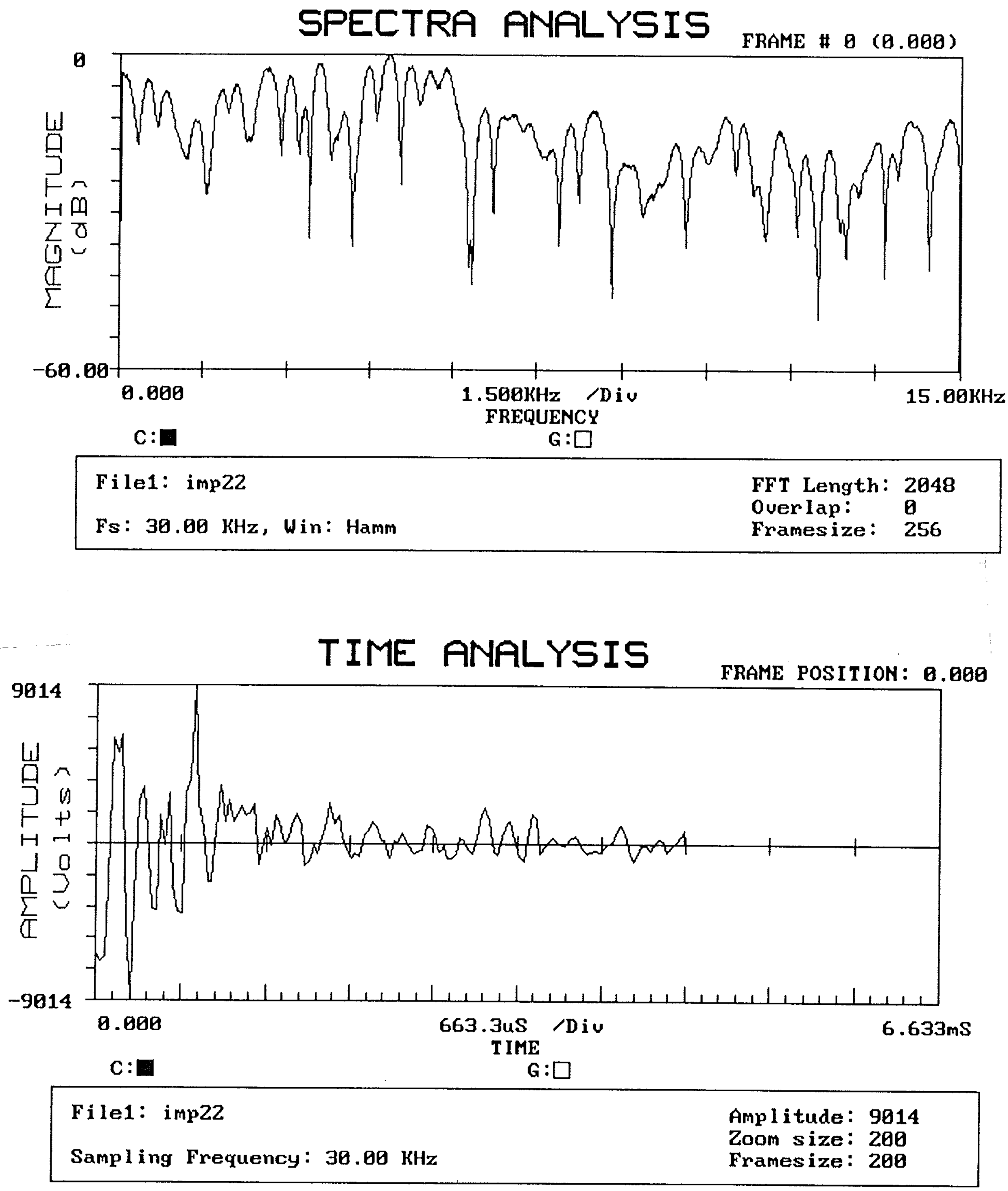


Figure 1b. Power spectrum and pressure-time waveform for impulse No. 2, impact welder at 1.5 m, with short B-duration.

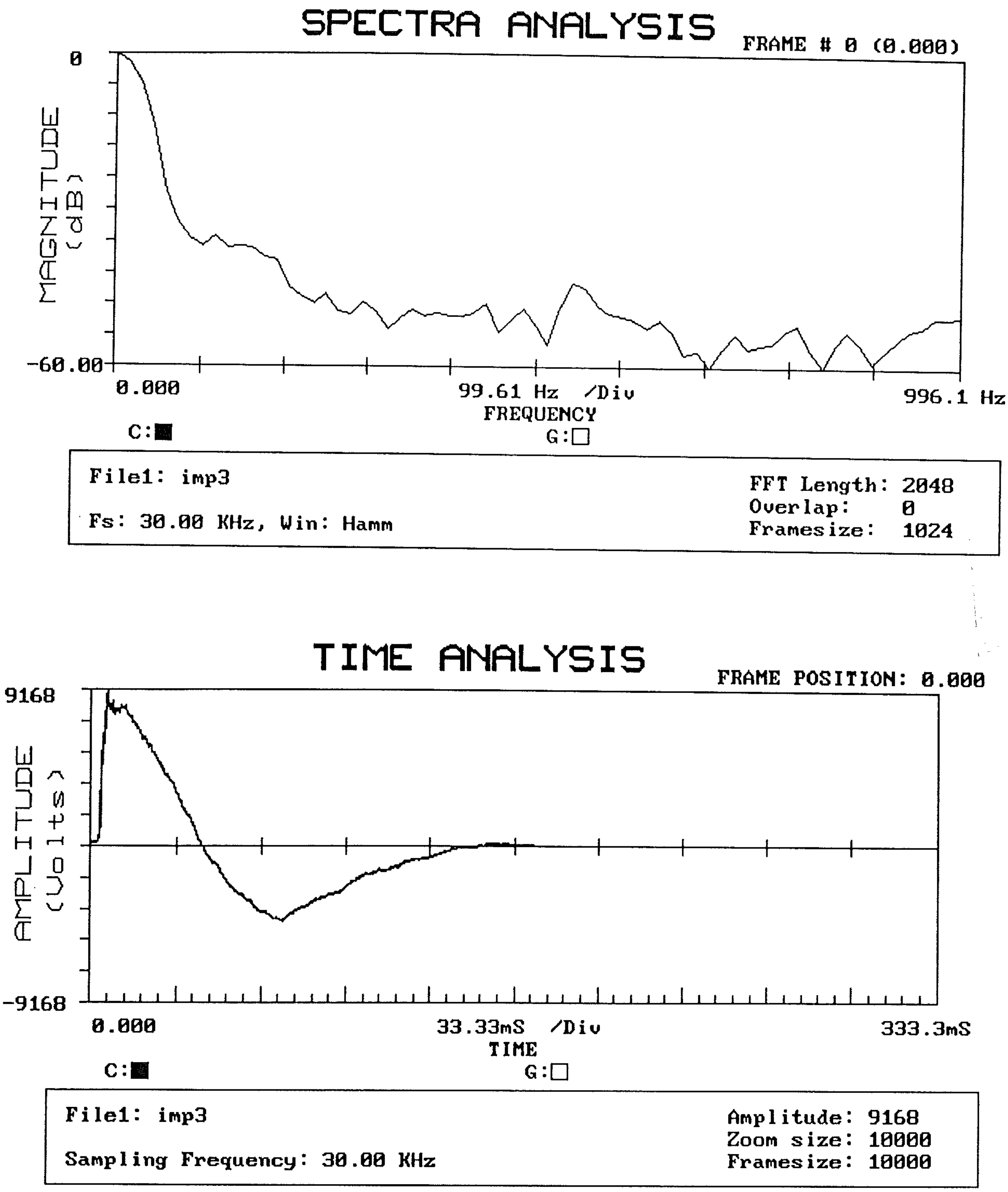


Figure 1c. Power spectrum and pressure-time waveform for impulse No. 3, 64 kg of plastic explosive at 500 m (low frequency Friedlander).

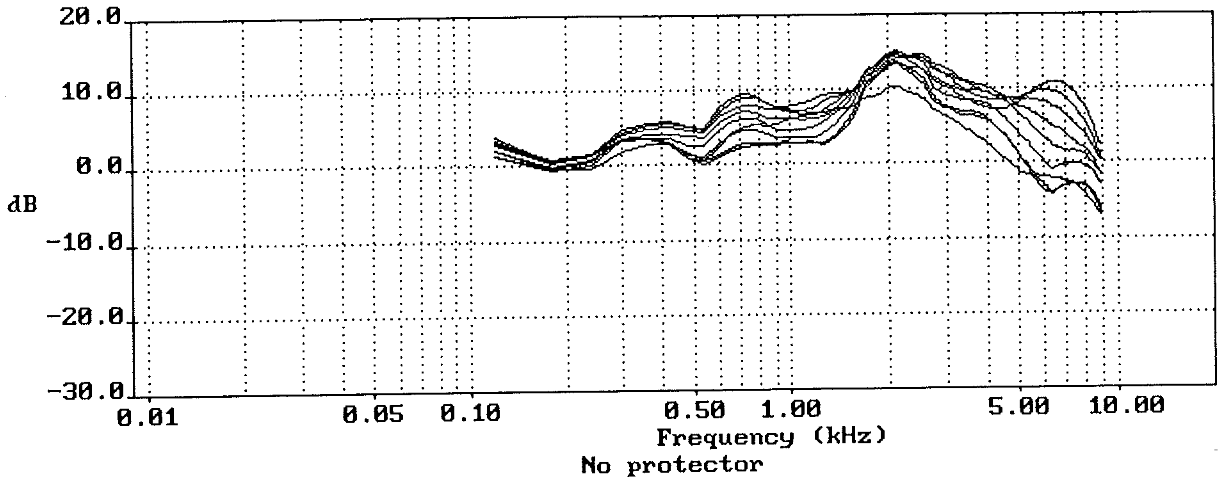
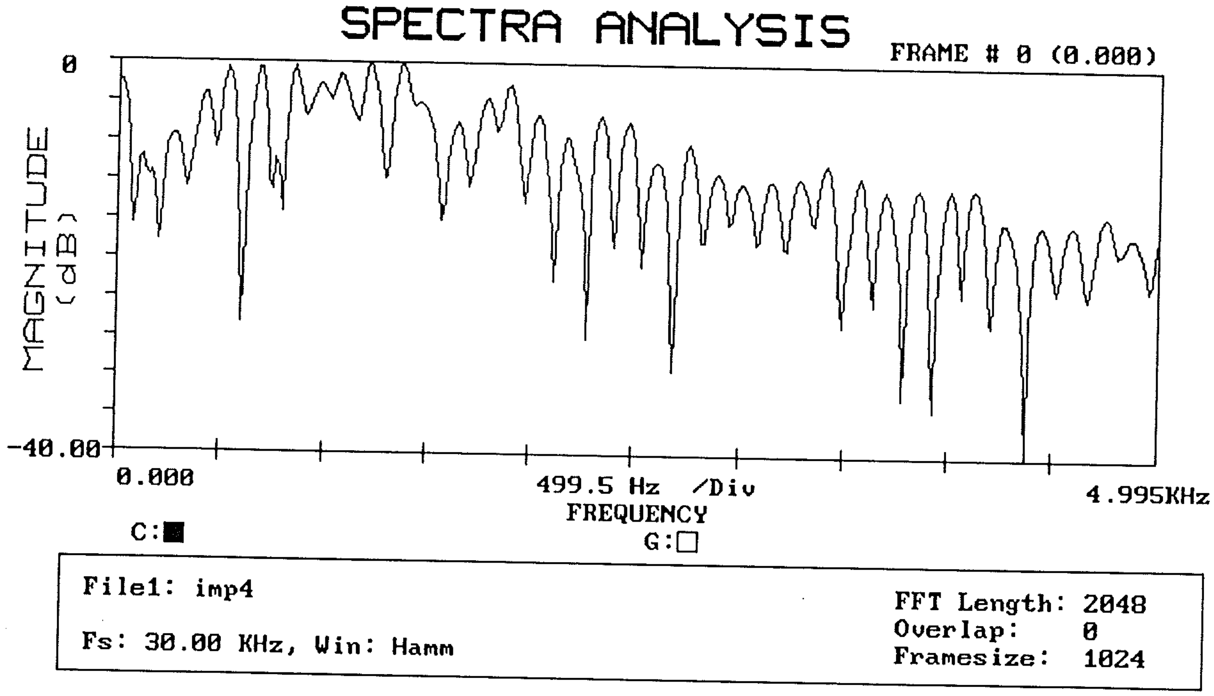


Figure 2. Frequency responses in the open ear canal for various angles of incidence. Mean over 16 subjects.



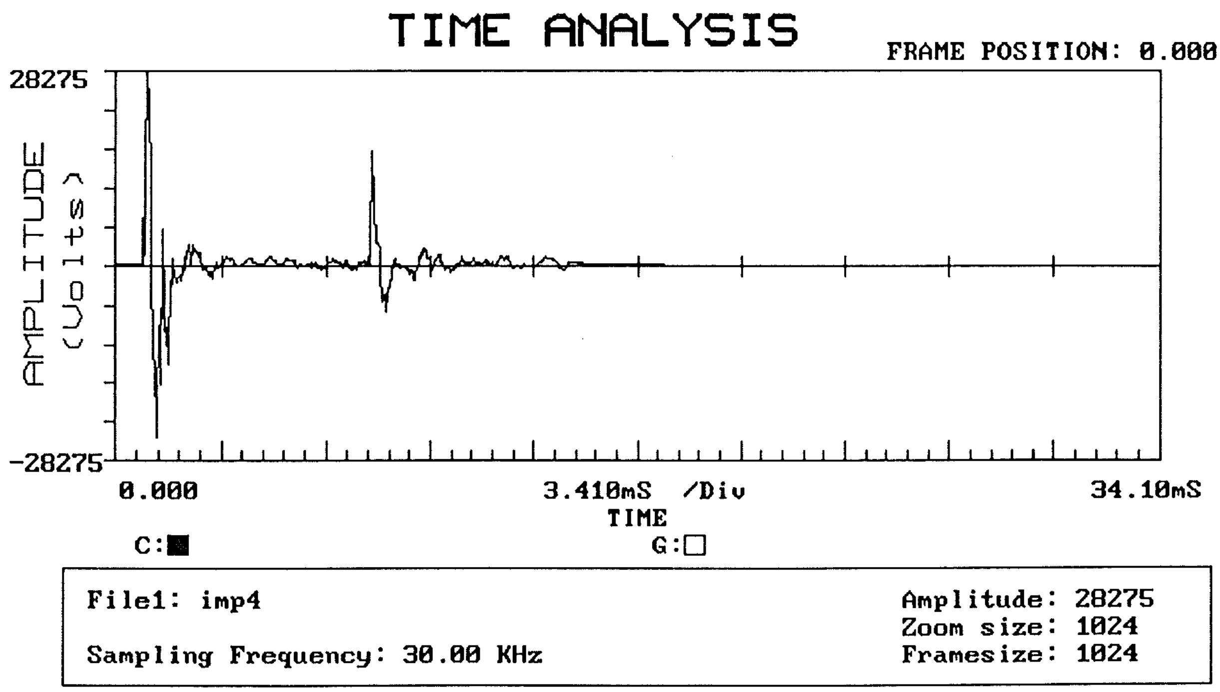


Figure 1d. Power spectrum and pressure-time waveform for impulse No. 4, pistol at 1 m, (high frequency Friedlander).

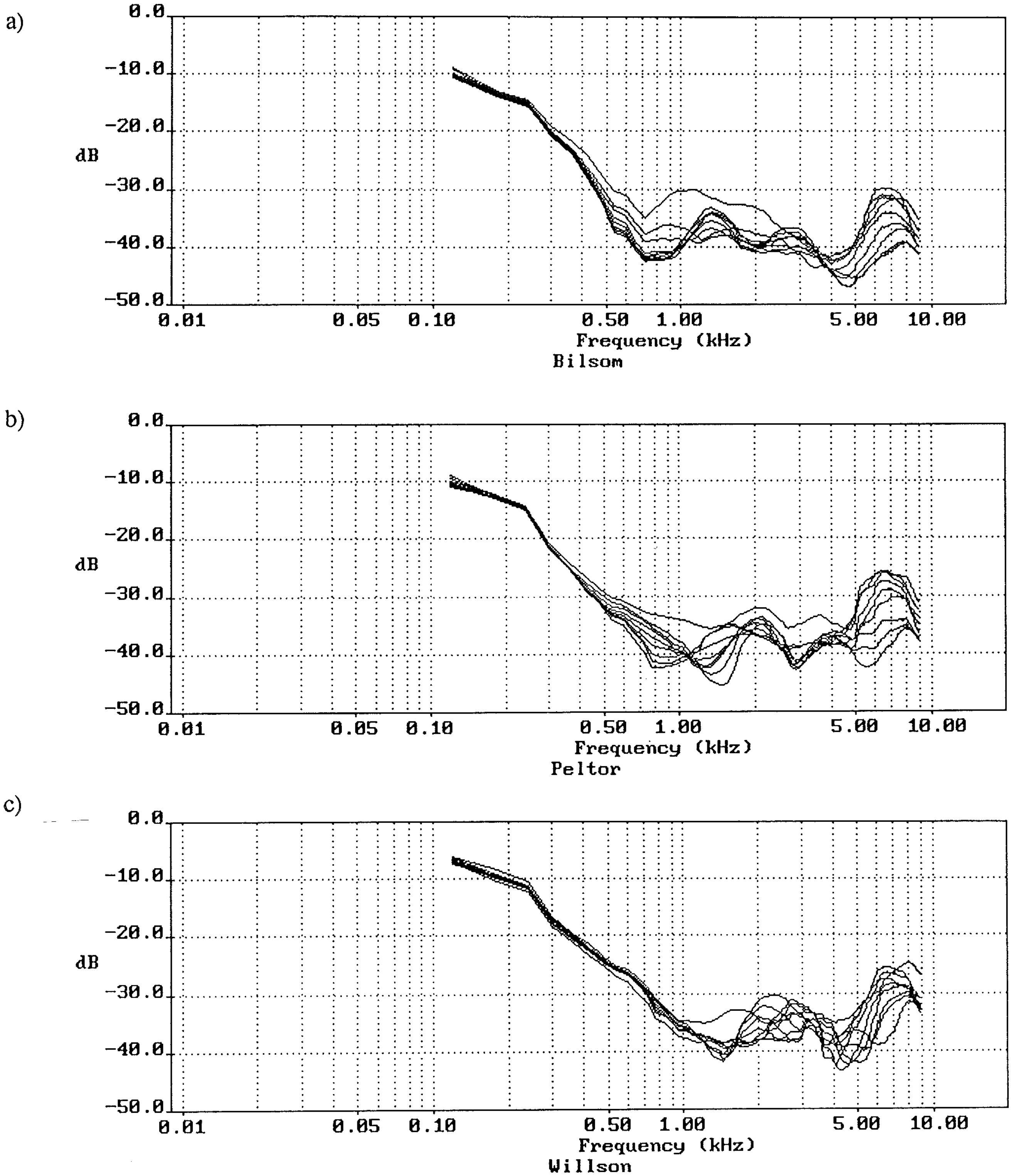
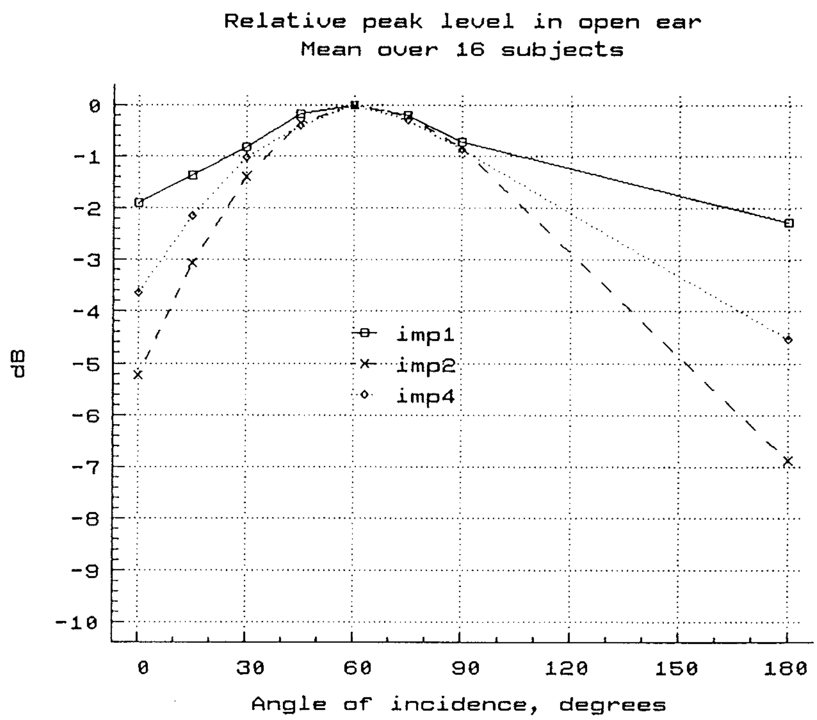


Figure 3a-c. Ear muff attenuation as a function of frequency for various angles of incidence. Mean over 16 subjects.
a) Bilsom Viking 2421, b) Peltor H7A and
c) Willson 358A.

a)



b)

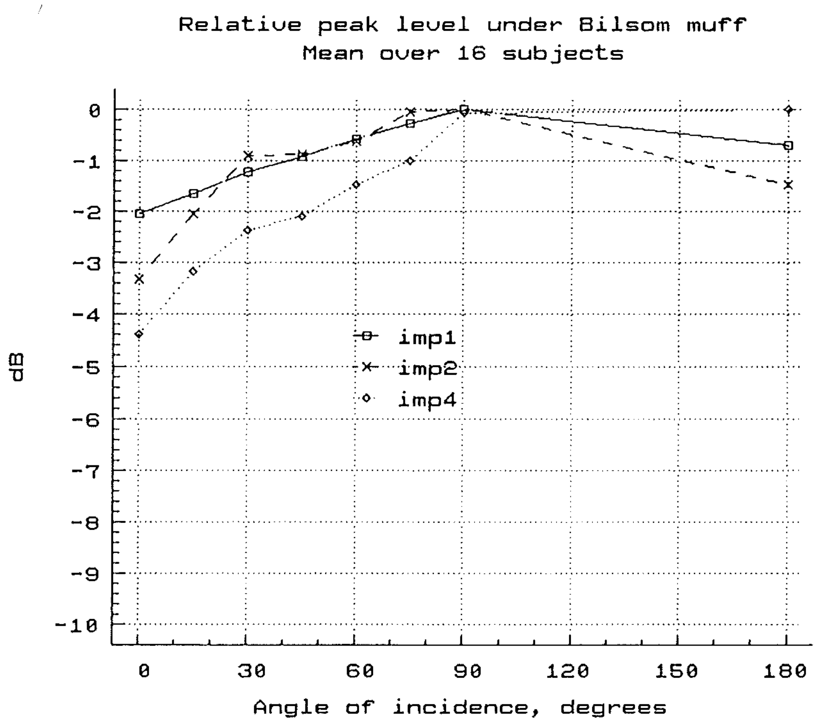
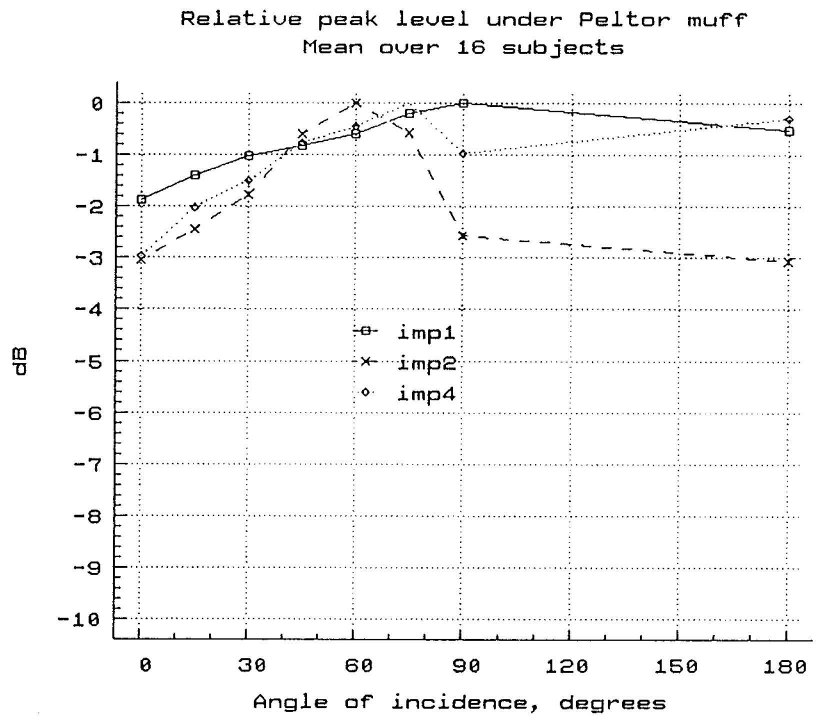


Figure 4a-d. Calculated peak levels in the ear canal as a function of angle of incidence and with type of impulse as a parameter. Mean over 16 subjects. a) in the open ear b) under Bilsom Viking 2421 c) under Peltor H7A and d) under Willson 358A.

c)



d)

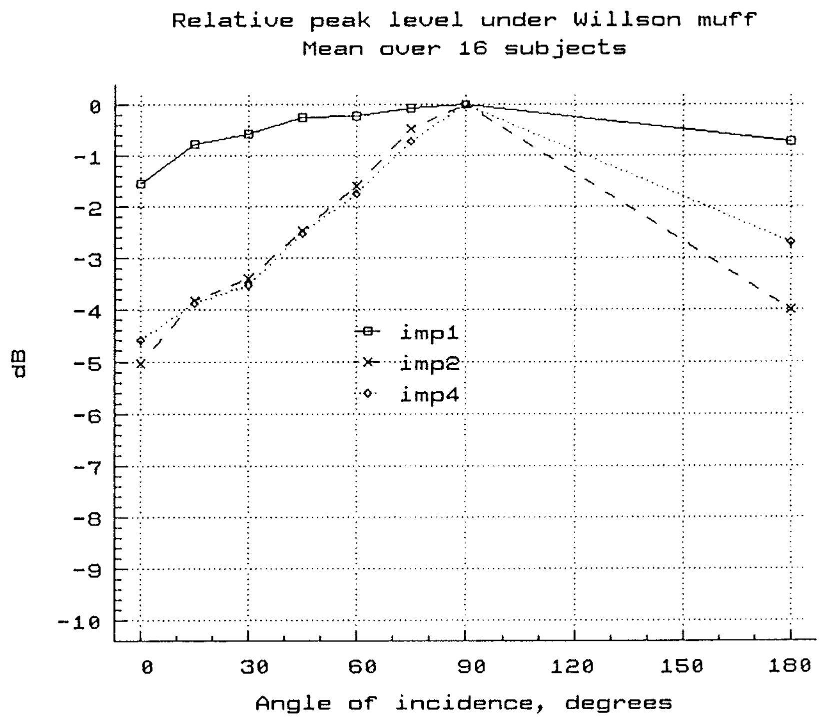
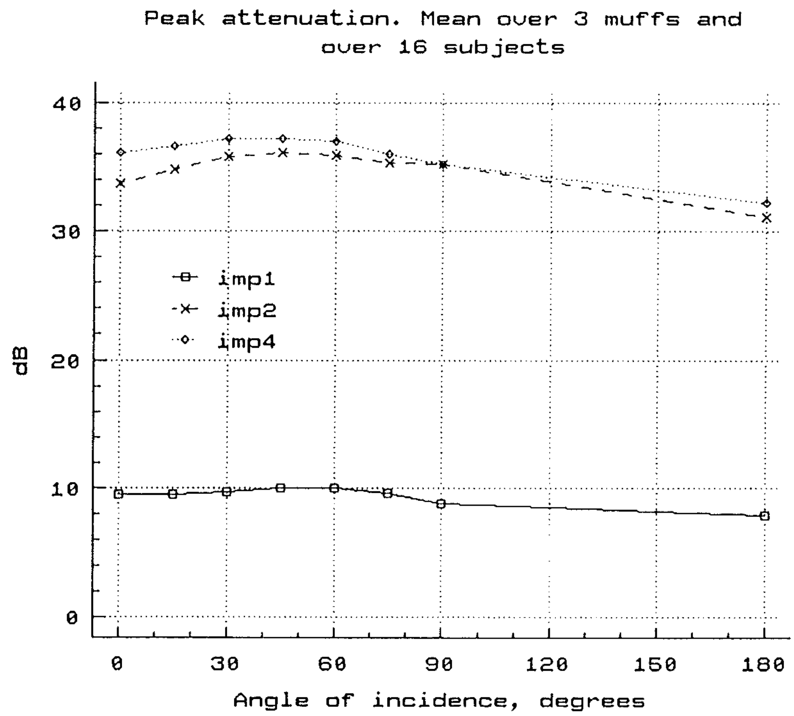


Figure 4a-d. (continued) Calculated peak levels in the ear canal as a function of angle of incidence and with type of impulse as a parameter. Mean over 16 subjects. a) in the open ear b) under Bilsom Viking 2421 c) under Peltor H7A and d) under Willson 358A.

a)



b)

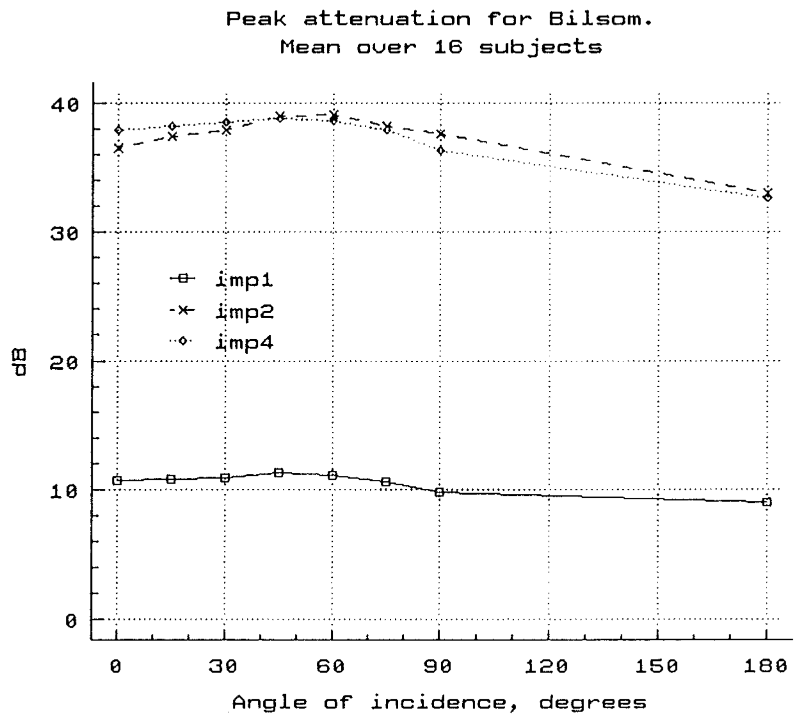
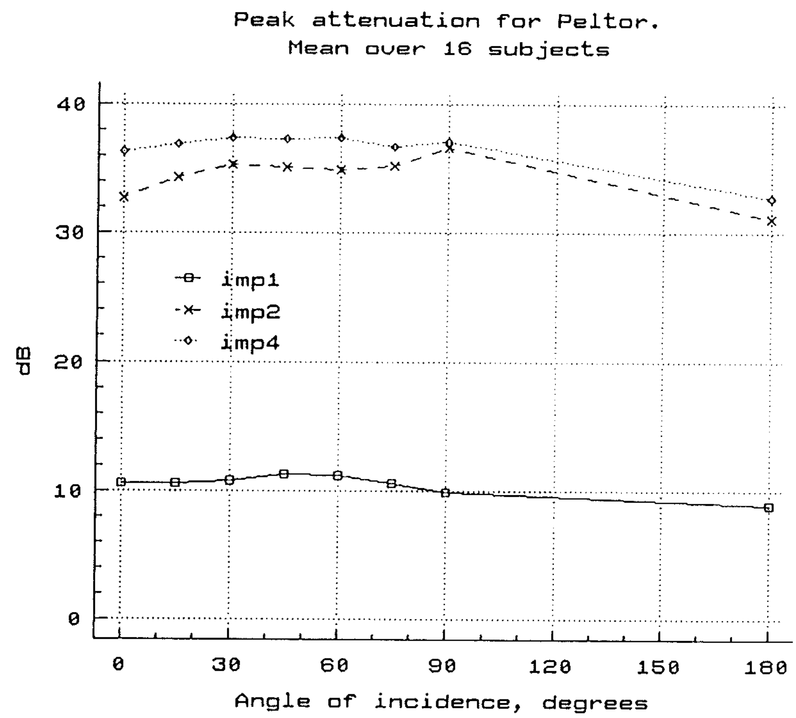


Figure 5a-d. Calculated peak attenuation as a function of angle of incidence and with type of impulse as a parameter. Mean over 16 subjects.
a) Mean over 3 types of muffs, b) Bilsom Viking 2421, c) Peltor H7A, d) Willson 358A.

c)



d)

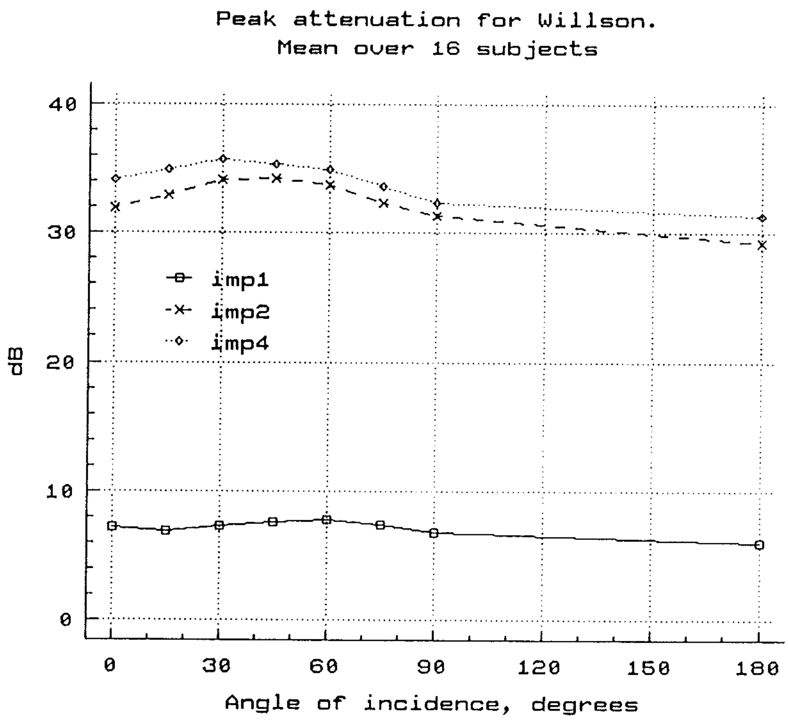
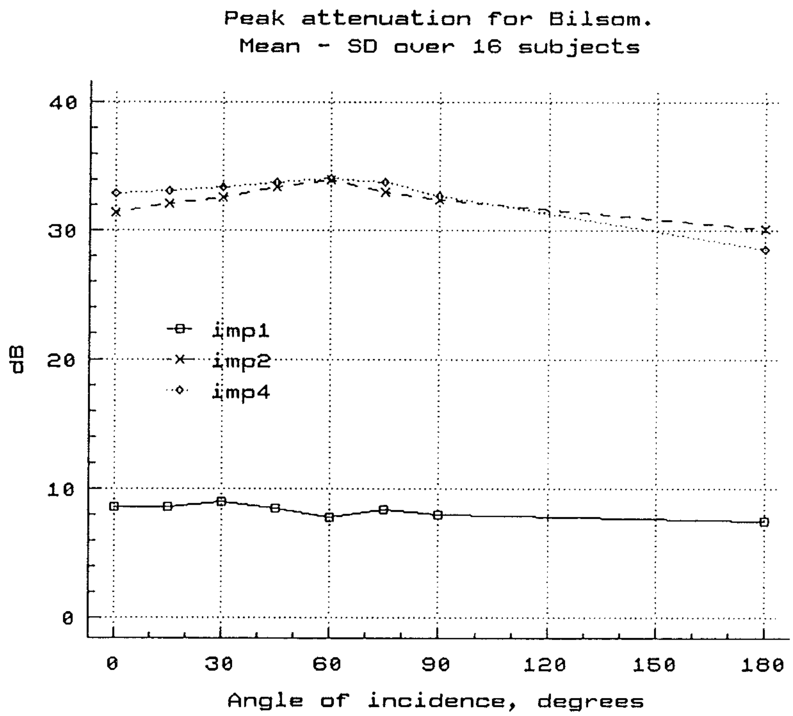


Figure 5a-d. (continued) Calculated peak attenuation as a function of angle of incidence and with type of impulse as a parameter. Mean over 16 subjects.

a) Mean over 3 types of muffs, b) Bilsom Viking 2421, c) Peltor H7A, d) Willson 358A.

a)



b)

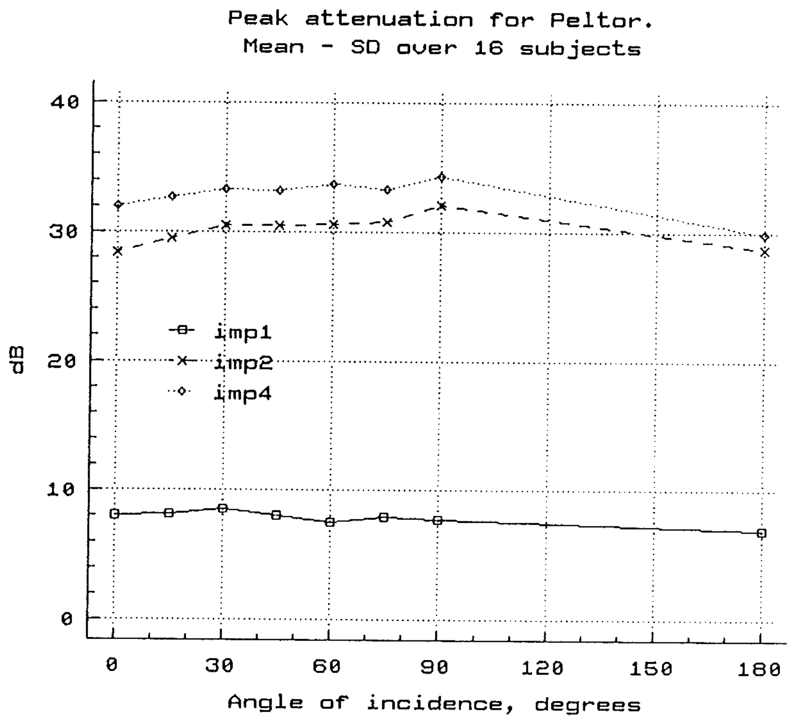


Figure 6a-c. Calculated peak attenuation as a function of angle of incidence and with type of impulse as a parameter. **Mean - SD** over 16 subjects. a) Bilsom Viking 2421 b) Peltor H7A c) Willson 358A.

c)

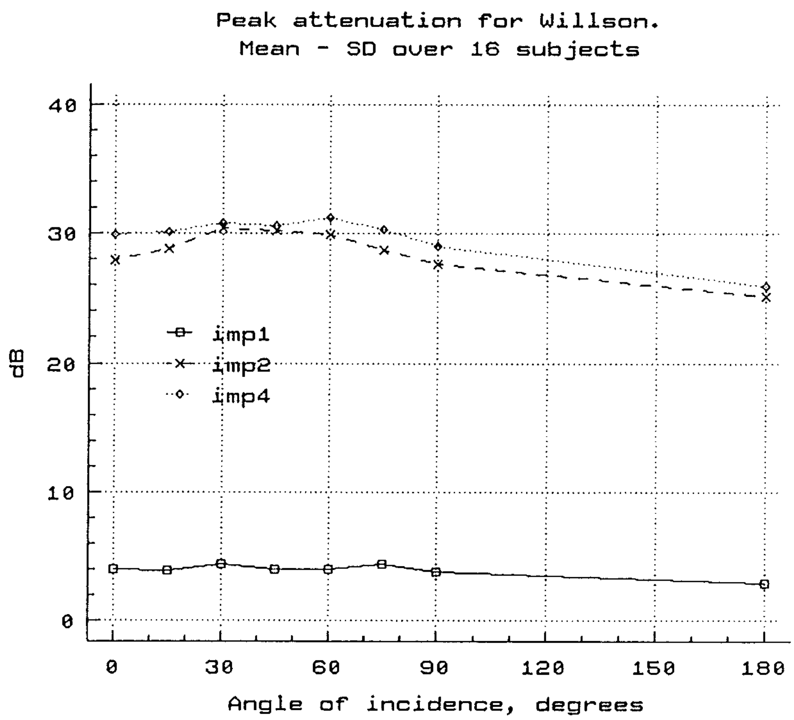


Figure 6a-c. (continued) Calculated peak attenuation as a function of angle of incidence and with type of impulse as a parameter. **Mean - SD** over 16 subjects. a) Bilsom Viking 2421 b) Peltor H7A c) Willson 358A.