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A hearing protector model for predicting impulsive noise hazard

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Reduction of impulsive noise hearing hazard by earplugs and earmuffs is calculated with an electro-acoustic lumped-parameter circuit-model of insertion-loss using real ear attenuation at threshold (REAT) data. It assumes energy flow into the protector occluded volume along three paths, each considered as a piston: 1) the rigid protector mass moving against the skin, 2) leakage at the support and 3) transmission through the protector material (a second piston within the rigid piston). Circuit elements are adjusted so loss matches REAT data assuming path 1 is important at low, 2 at middle and 3 at high frequencies. Applying the model to 384 REAT data-sets for ANSI S12.6 method B naïve users gives statistical frequency distributions of occluded volume and leakage elements. For a given free-field impulsive noise, the model pressure predictions under the protector are compared to measurements acoustical manikin ears to check validity of assumptions. The hearing hazards of the measured waveforms and the predicted waveforms are calculated with our previously developed AHAAH ear model (Auditory Hazard Analysis Algorithm for Humans). The result is a cumulative frequency distribution of hazard based on user fit data useful in finding the best protector for a given impulsive noise.

1. INTRODUCTION

It is certain that combat with energetic weapons damages unprotected hearing and reduces military performance, but soldiers are reluctant to wear recommended protection since resulting isolation also reduces military performance. Solution of this dilemma would be to permit acoustic transmission at low levels while providing protection by means of a non-linear orifice in the combat arms earplug, a peak-clipping pass-through headphone or a passive protector custom designed for the weapon. To support these approaches, we made a hearing protector (HP) model for use with our previously developed hearing hazard model[1], AHAAH (Auditory Hazard Assessment Algorithm for Humans). AHAAH predicts hazard based on pressure waveforms measured in the free field or under hearing protective devices on real ears or acoustic manikins and has been validated against losses for known human exposures[2].

The HP model extends AHAAH application to improving weapon and HP designs by predicting protected responses to free-field waveforms using commonly available REAT HP data. This paper gives the history of HP models, derives the model equations and describes component adjustments to match the REAT data. Applying the model to 384 REAT data sets on four different HPs of the Interlab study[12] gives fit and hazard distributions for a selected weapon waveform.

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As an intermediate check of validity, the paper compares predictions to measurements on a manikin auditory test fixture (ATF). It also shows how the HP model can be used with the AHAAH model to assess given hearing protectors for a given free-field pressure waveform.

1.1 Background

Studies[3-7] of sound transmission through the ear or a HP often start with schematic diagrams based on electro-acoustic (EA) analogies between acoustical elements and their electrical counterparts identified by anatomical and physical structure and shown in Fig. 1. The method tracks energy flow through fluid and solid pathways as well as at electrical transducers such as microphones and loudspeakers. The equations of motion for sound in these devices are the same as the electrical network equations for voltages and currents in the circuit[8,9]. In general, some elements may not be constant depending on their displacement, velocity or temperature, but even so, this influence can be included in the circuit differential equations and solved by numerical integration to give pressure under the HP. For the initial investigation purpose of this paper, only linear passive hearing protectors will be considered. Assuming these elements are fixed at low stimulus levels, these equations can be transformed by Fourier analysis into complex polynomials which can be solved and compared to measured transfer function magnitudes and phases between various parts of the protector. These constant values serve as the low level constant part of variable coefficients for the time domain calculations at higher level excitation.

Previous work[3-5] has established the first two paths of this model in Fig. 2. The first path of both earmuff and earplug models is a main piston formed by the protector mass, L_m supported by the stiffnesses, K_{cu}, K_{sk} and damping, R_{cu}, R_{sk} of the cushion and skin. This piston is rigid, leak-free, and moves under pressure from the external sound to compress the occluded volume element, K_V behind with resulting sound pressure at the eardrum. It has a second-order low-pass frequency response with cutoff frequency of about 500 Hz for earmuffs and 2 kHz for earplugs. The piston moves to compress the cushion and skin for the earmuff while it shears the protector material and skin for the earplug. In the case of shear between the earplug and lining of the earcanal, only the combined stiffness and resistance was given so it is assumed that the cushion resistance and stiffness are each ten times greater than the skin values which then substitute for the combined effect values.

At low frequencies, pressure division between the occluded and support stiffnesses gives an attenuation level of $20*\log_{10}(K_V/(K_V + K_{cu\_sk}))$ in the rigid piston path. Here $K_{cu\_sk} = K_{cu}K_{sk}/(K_{cu} + K_{sk})$ is the combined cushion-skin stiffness and is typically ten times greater than K_V. Leakage at the skin-protector contact is modeled in the second path as an air-plug piston with mass, L_{lk} moving against the boundary resistance, R_{lk} in a tube with flow bypassing the main piston at low-frequencies[8]. It has been pointed out that at frequencies above the main piston resonance there is transmission through the protector material due to modal vibrations[4,5]. To account for this, a material path was added but was only described by an impedance, Z_{mat}[3,6]. This third path is shown in Fig. 2 as a secondary piston of mass, L_{mat} supported by stiffness and viscous elements, K_{mat} and R_{mat} within the otherwise rigid main piston. This additional pathway concept can be extended to include transmission in the earmuff cushion or bone-conduction into the ear-canal as shown in Fig. 1.

2. METHOD

In the model, pressures are analogous to voltages (v or V) and volume velocities are analogous to currents (i or I) as shown in Fig. 2. Lower case symbols denote quantities in the time domain while upper case symbols are transformed amplitudes in the frequency domain. Time domain differential equations of motion are given in equations (1) - (7) while frequency domain amplitudes are given by equations (8) - (14). Here j is the imaginary unit and $\omega = 2\pi f$ is the angular frequency related to the cyclic frequency, f. Circuit element values for generic earplugs and earmuffs are given in Tables 1 and 2 and serve as starting estimates for the model supplemented by specific information on protector mass or occluded volume if known.

$$i_0 = i_1 + i_2 + i_3 \tag{1}$$

$$v_{out} = K_V \left(q_1 + q_2 + q_3\right) \tag{2}$$

$$v_1 = v_{in} - v_{out} \tag{3}$$

$$\frac{di_1}{dt} = \left(v_1 - R_{cu} i_4 - K_{cu} q_4\right) / L_m \tag{4}$$

$$\frac{di_2}{dt} = \left(v_1 - R_{lk} i_2\right) / L_{lk} \tag{5}$$

$$\frac{di_3}{dt} = \left(v_1 - R_{mat} i_3 - K_{mat} q_3\right) / L_{mat} \tag{6}$$

$$\frac{di_4}{dt} = \frac{\left(R_{sk} \frac{di_1}{dt} + K_{sk} i_1 - \left(K_{cu} + K_{sk}\right) i_4\right)}{\left(R_{cu} + R_{sk}\right)} \tag{7}$$

$$I_0 = I_1 + I_2 + I_3 \tag{8}$$

$$V_{out} = K_V I_0 / j\omega \tag{9}$$

$$V_1 = V_{in} - V_{out} \tag{10}$$

$$V_1 = j\omega L_m I_1 + \left(R_{cu} - jK_{cu}/\omega\right) I_4 \tag{11}$$

$$V_1 = \left(j\omega L_{lk} + R_{lk}\right) I_2 \tag{12}$$

$$V_1 = \left(j\omega L_{mat} + \left(R_{mat} - jK_{mat}/\omega\right)\right) I_3 \tag{13}$$

$$0 = \left(R_{cu} - jK_{cu}/\omega\right) I_4 + \left(R_{sk} - jK_{sk}/\omega\right)\left(I_4 - I_1\right) \tag{14}$$

The pressure under the protector in response to a given free-field pressure is found by integrating equations (1) - (7) using the fourth-order Runge-Kutta method with adaptive step-size control[10,11]. Assuming constant coefficients at low excitation levels, the Fourier transform gives the set frequency-domain equations (8) - (14). In these equations, the ratio of the output voltage, V_{out} to input voltage V_{in} gives the linear transfer function for the insertion loss model. The magnitude of this transfer function for the individual pathways and their combination is shown in Fig. 3, 4 and 5 for a fitting procedure applied to four samples of each of three HPs from the Interlab study. The protectors were the V-51R and E.A.R. earplug and the Bilsom UF-1 earmuff. The sum of squared deviations between the model and the REAT data values is minimized by iteratively changing the tabular values.

The rigid piston response is assumed to always be present but to be bypassed by leakage or material path transmission. In addition to restriction of its known mass and occluded volume, the supporting stiffness and resistance are constrained to a range of values from 1/3 to 3 times the tabular values. The leak and material path values are then freely adjusted to account for any excess transmission.

For the V-51R earplug in Fig. 3A and 3D the three paths dominate in their respective frequency regions. In Fig. 3B the leak bypasses the main piston and in Fig. 3C the leak is minimal so that the main piston controls the low to mid frequency response. In all four V-51R cases the material transmission shows a sharp resonance at 8kHz with Q of about 8. For the E.A.R. earplug in Fig. 4 the leak is only present for low frequencies in Fig. 4C. The main piston transmission is the same in Fig 4. A, B and C but is lower in Fig. 4D indicating a stiffer support with more loss at frequencies below resonance. In all four cases the material piston resonance is below 8kHz with a lower Q of about 3. For the Bilsom UF-1 earmuff in Fig. 5 the leak dominates for all four cases for frequencies below 500 Hz. Evidence of a leakage resonance is seen at 900Hz in Fig. 5B. The main piston transmission is only seen at 2 kHz in Fig. 5D. The material piston resonance in all cases is near 5kHz with a lower Q of about 1. Of the three protectors the variability was greatest for the V-51R due mostly to leakage variations. The E.A.R. earplug showed the least variability since the expansion of the foam material generally produced a good seal.

This fitting procedure was applied to the 384 REAT data sets for the four protectors tested in the Interlab study, the three previously mentioned and including the EP-100 earplug. The statistical frequency distributions of two model values, the occluded volume compliance (compliance is the reciprocal of stiffness) and the leak resistance is shown in Fig. 6A and 6C. Of the three earplugs, the V-51R has the greatest variability in occluded volume and a high occurrence of low leak resistance indicating poor fit. The E.A.R. leak resistance is uniformly distributed at much higher resistance. The Bilsom earmuff has larger occluded volume and more skin-surface area for leak shown in Fig. 6B and 6D. Leakage at the earmuff seal is greater than for the earplugs limits loss below 80 Hz.

3. RESULTS

For all 384 data sets the pressure response under each protector fit by the above procedure was calculated for a free-field rifle pressure and applied as an attenuated free-field pressure waveform to the AHAAH model to calculate the unwarned and warned auditory risk of the protected exposures. The AHAAH model allows the aural reflex to be activated when the shooter expects the blast. The model sums the auditory risk units (ARU) for each exposure with a maximum allowable value of 500. A cumulative distribution of risk for each protector is shown in Fig. 7. At the 90% level, the Bilsom earmuff and E.A.R. earplug have the lowest hazard for both unwarned and warned protected hazard while the EP-100 and V-51R hazards are substantially higher due to poorer fit.

Fig. 8 shows predictions of waveforms under earmuffs in response to three weapon waveforms. In Fig. 8A a RACAL earmuff worn under a helmet was exposed to a 155mm howitzer, in Fig. 8B a COMTAC earmuff was exposed to a shoulder-fired rocket fired from an enclosure and in Fig. 8C a Peltor Sound Trap earmuff was exposed to a rifle. In all cases the earmuff was mounted on a manikin.

4. CONCLUSIONS

1. Hearing protector insertion loss and known acoustical values lead to electro-acoustic model values by a fitting procedure.

2. With a free-field pressure stimulus, the electro-acoustic model gives the hearing protector response. Using this waveform as an attenuated free-field stimulus the AHAAH model gives the response under the protector on the head, and also the hearing hazard.

3. Applying the hearing protector model to multiple insertion loss cases gives the distributions of electro-acoustic values which describe the variability of fit. Applying these multiple fits to given free-field waveform gives cumulative distributions of hearing hazard which describe the percentage of the population that are protected.

5. REFERENCES

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Table 1 - Circuit element values for a generic earmuff[3, 6].

1.13E+05	Kcu dyne/ cm^5	Acoustic area=Pi*Sqr(3.5cm)
5.40E+01	Rcu dyne-sec/cm^5	
6.75E+04	Ksk dyne/ cm^5	(leak path length = 1 cm)
2.50E+02	Rsk dyne-sec/cm^5	0.1 0.2 0.5 1.0 2.0 5.0 10 20(leak diameter mm)
1.65E-01	Llk g/cm^4	2.0E1 5.0E0 8.0E-1 2.0E-1 5.0E-2 8.0E-3 2.0e-3 5.0e-4
2.31E+02	Rlk dyne-sec/cm^5	7.3E5 4.6E4 1.2E3 7.3E1 4.6E0 1.2E-1 7.3e-2 1.2e0
4.05E-02	Lm g/cm^4	60 gram mass
1.42E+04	Kv dyne/ cm^5	Rho*C^2 /Volume for 100cm^3 volume
6.12E+03	Rmat dyne-sec/cm^5	
8.04E-02	Lmat g/cm^4	
1.69E+08	Kmat dyne/ cm^5	

Table 2 – Circuit element values for a generic earplug[3,6].

3.42E+08	Kcu dyne/ cm^5	Acoustic area=Pi*Sqr(0.375cm) Rho=1.15e-3g/cm3 C=3.52e4cm/sec
7.69E+05	Rcu dyne-sec/cm^5	
3.42E+07	Ksk dyne/ cm^5	(leak path length = 1 cm)
7.69E+04	Rsk dyne-sec/cm^5	0.1 0.2 0.5 1.0 2.0 5.0 10 20(leak diameter mm)
2.54E+01	Llk g/cm^4	2.0E1 5.0E0 8.0E-1 2.0E-1 5.0E-2 8.0E-3 2.0e-3 5.0e-4
1.88E+04	Rlk dyne-sec/cm^5	7.3E5 4.6E4 1.2E3 7.3E1 4.6E0 1.2E-1 7.3e-2 1.2e0
10.3E+00	Lm g/cm^4	2 gram mass
2.15E+06	Kv dyne/ cm^5	Rho*C^2/Volume, Volume = 0.66cm^3, Rho*C^2=1.42E6 dyne/cm^2
6.12E+03	Rmat dyne-sec/cm^5	
8.04E-02	Lmat g/cm^4	
1.69E+08	Kmat dyne/ cm^5	

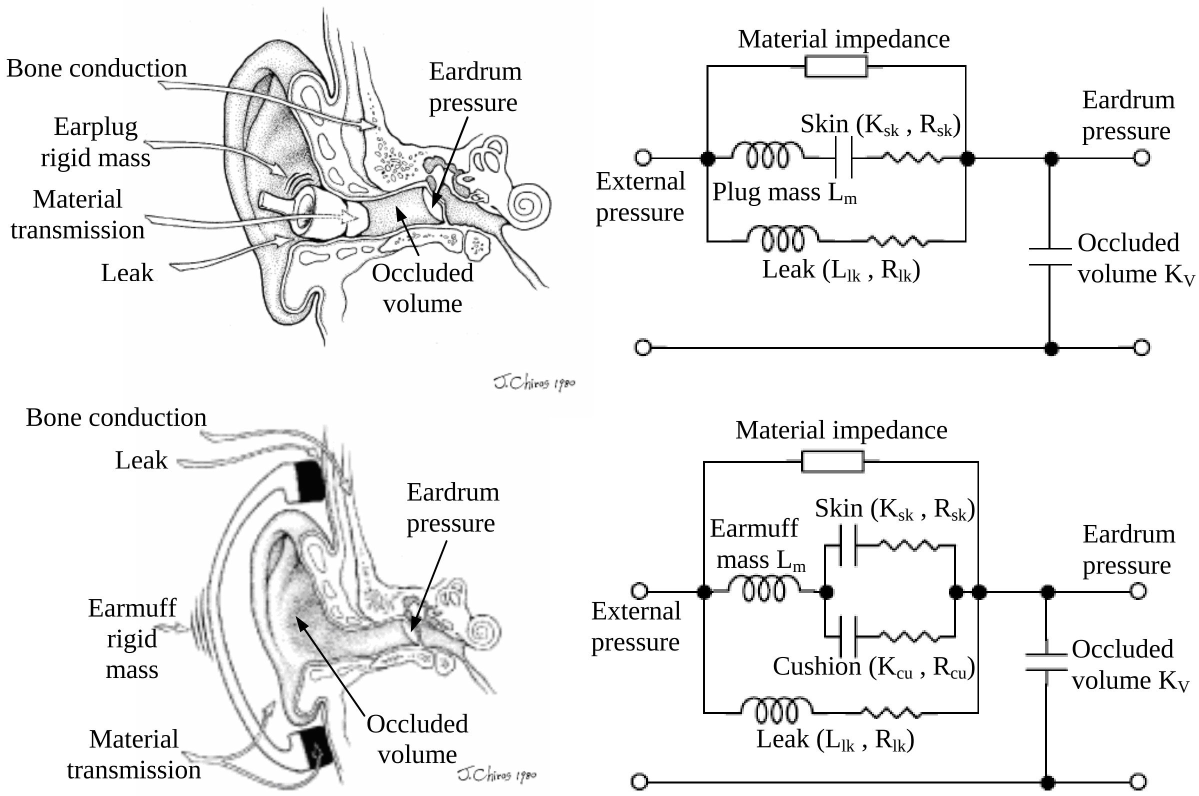

Fig. 1 - Acoustical and electrical diagrams of earplug and earmuff showing model elements for energy flow paths.

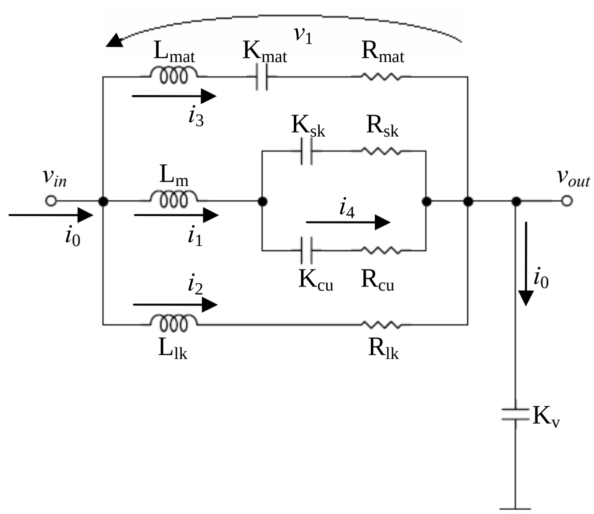

Fig. 2 - Schematic diagram for the three piston hearing protector model.

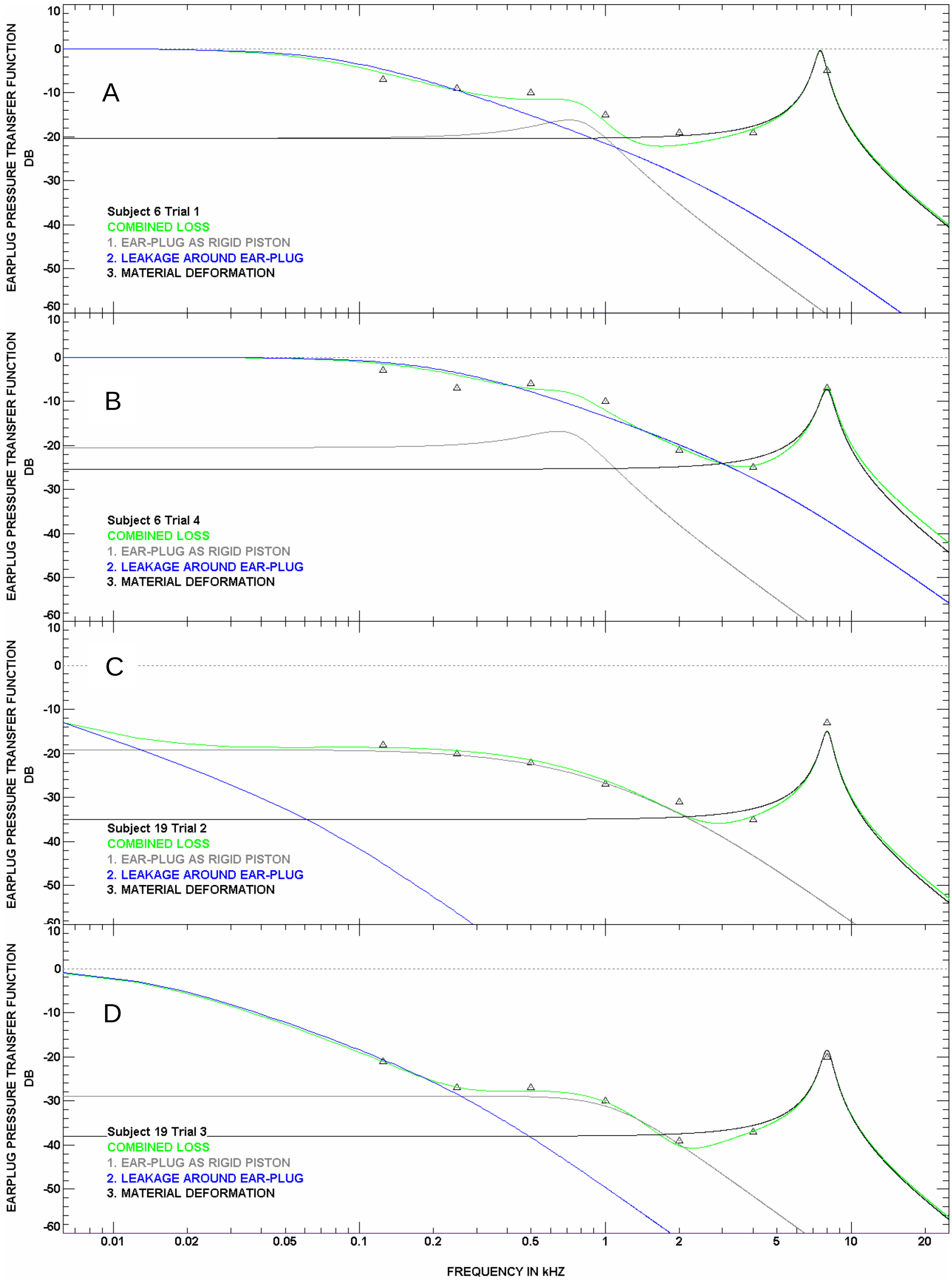

Fig. 3 - Model fits to selected data for the V-51R earplug.

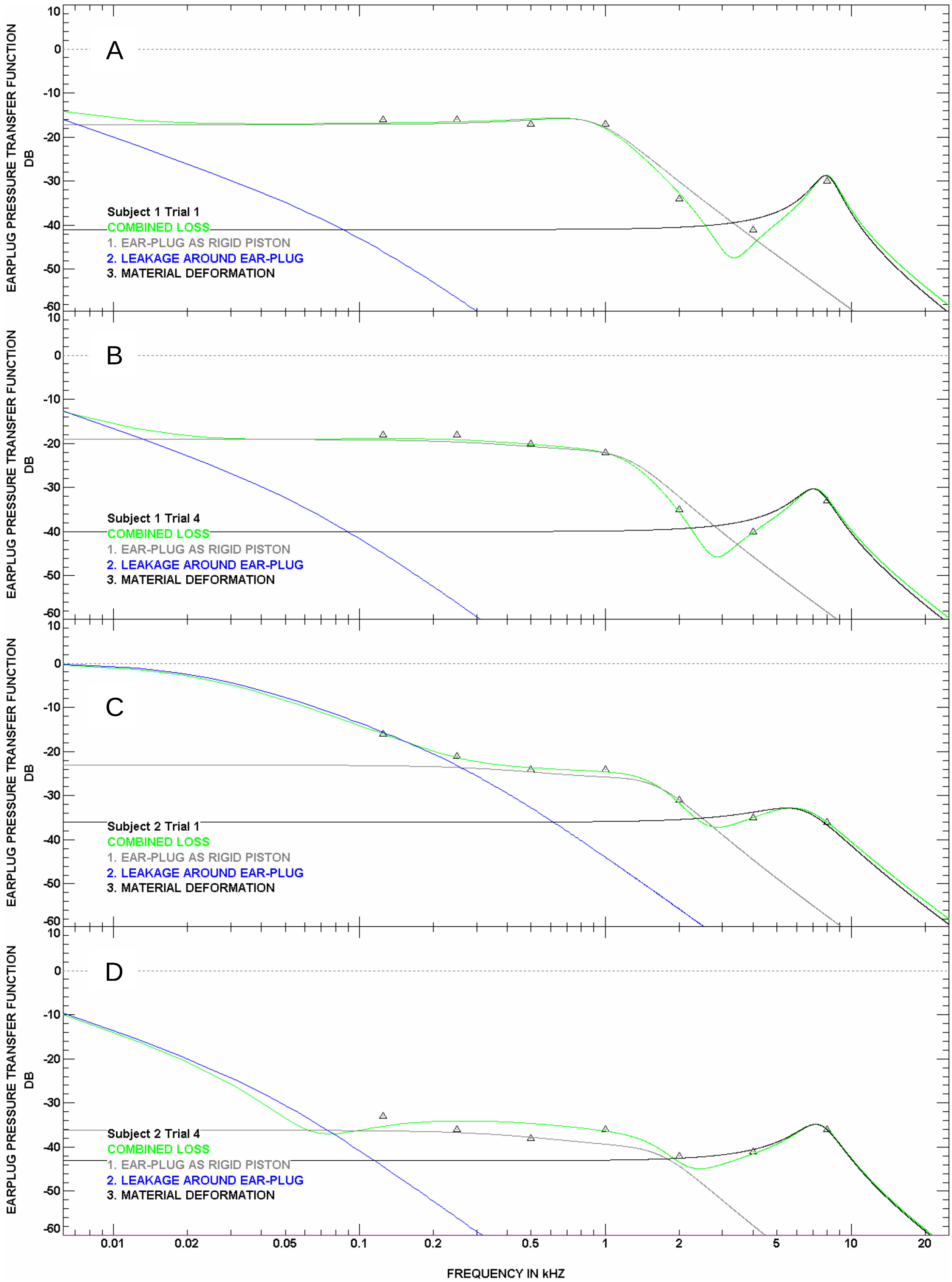

Fig. 4 - Model fits to selected data for the E.A.R. earplug.

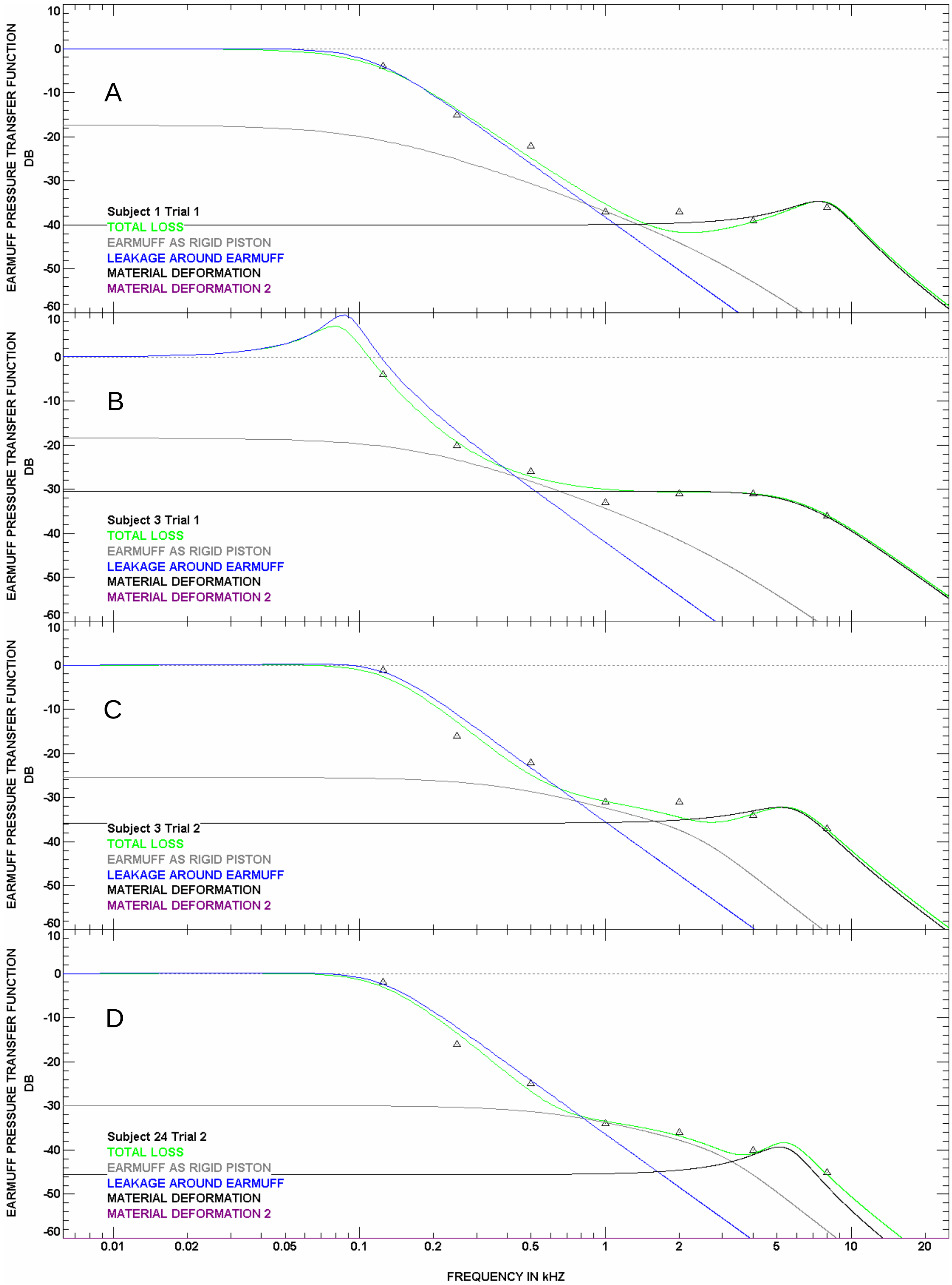

Fig. 5 - Model fits to selected data for the Bilsom UF-1 earmuff.

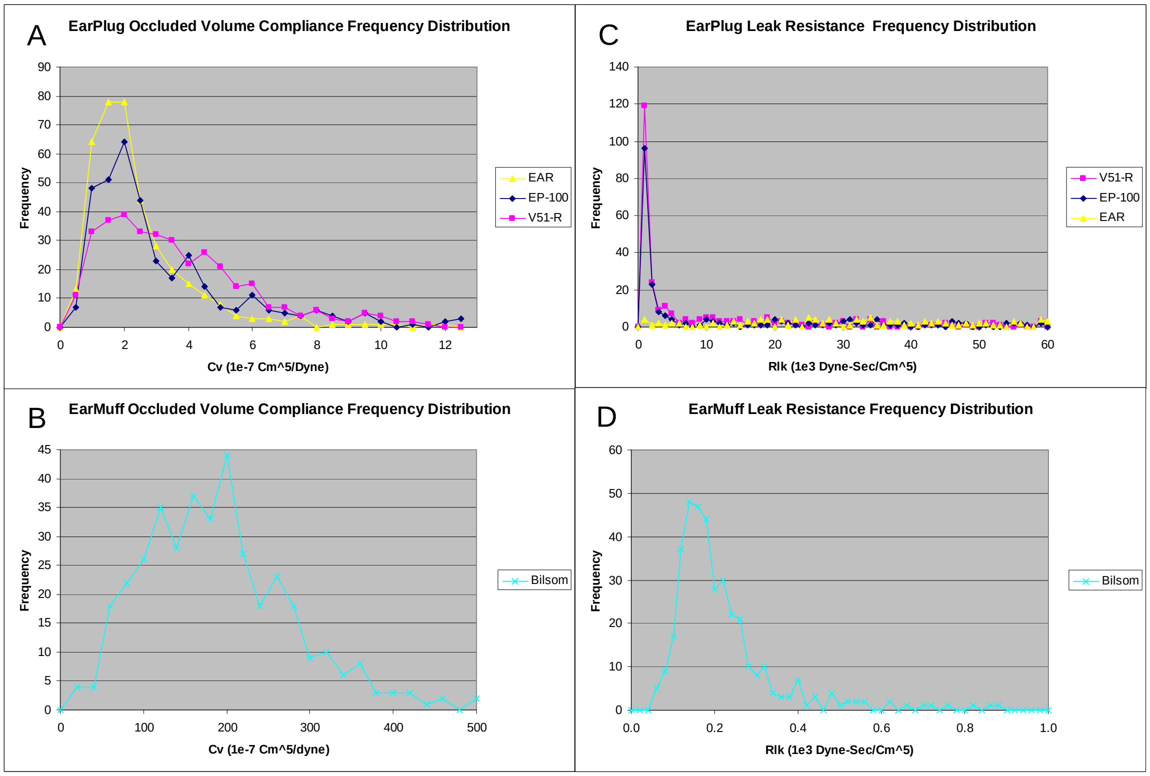

Fig. 6 - Frequency distributions of model values for the 384 subjects and four protectors.

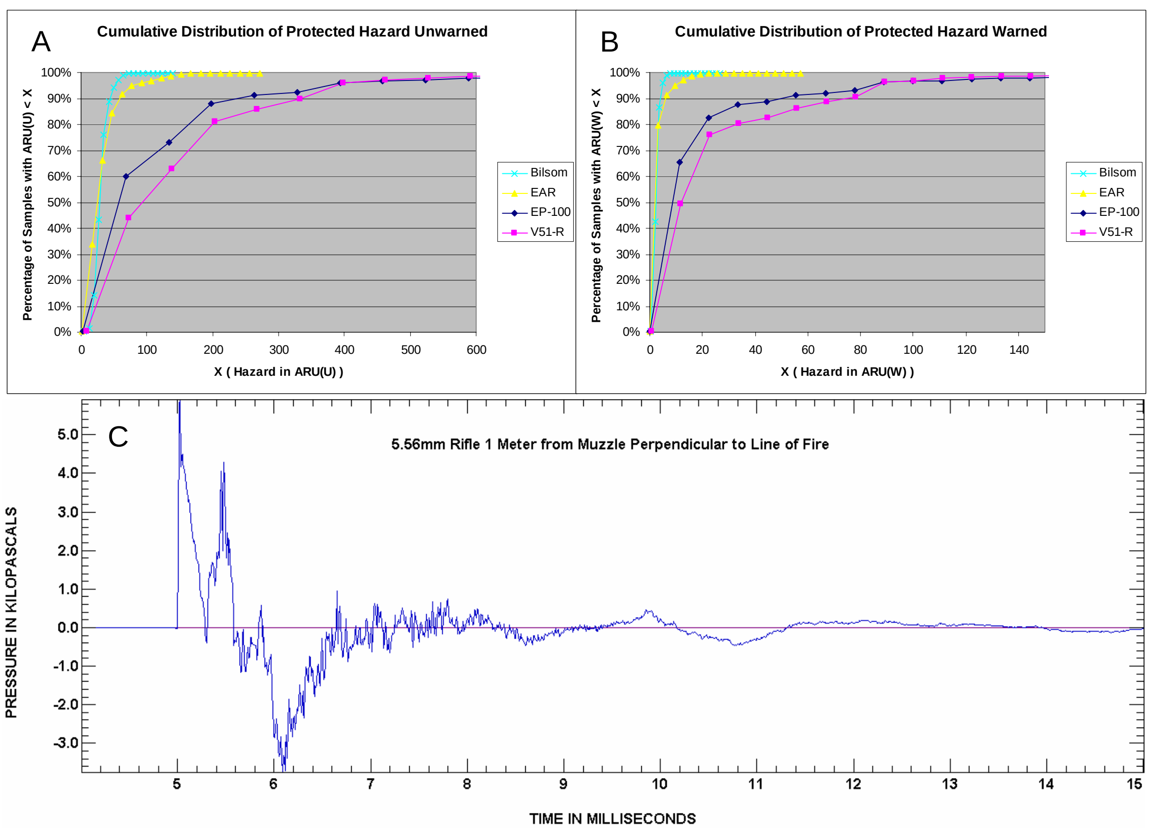

Fig. 7 - Cumulative distributions protected hazard for protectors when exposed to a rifle.

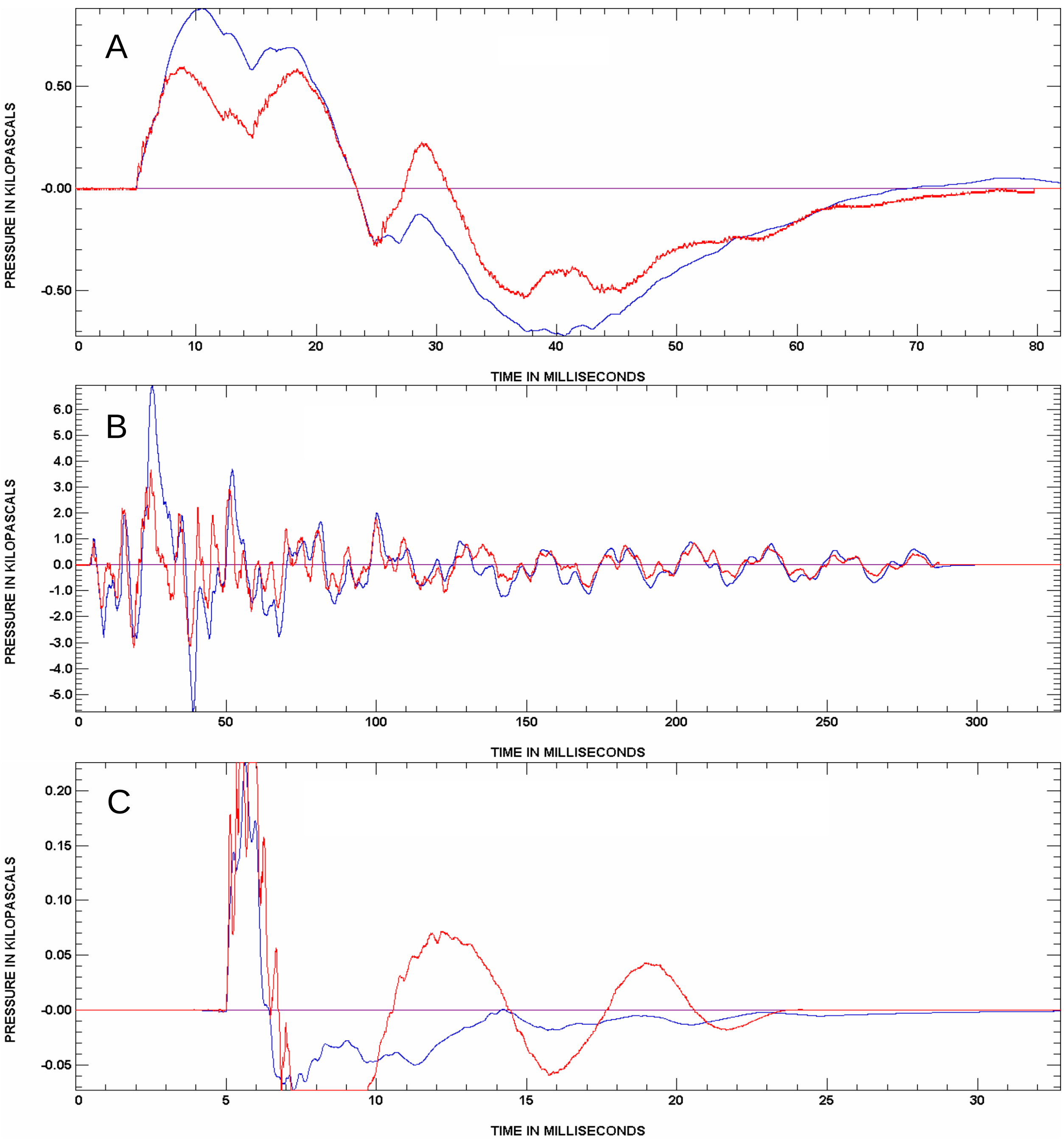

Fig. 8 - Comparison of model predictions (blue curve) to measurement under earmuffs (red curve) in response to a 155mm Howitzer in A, a shoulder-fired rocket in an enclosure in B, and a rifle in C.