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Expandable Earplug With Smart Custom Fitting Capabilities

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Abstract

For hearing protection to be made effective, the research needs established by NIOSH (National Institute for Occupational Safety and Health) are to find a way for workers to be individually fitted and to offer them increased comfort and the ability to hear speech and warning signals.

To address these issues, a new concept has been developed; a re-usable earplug that is custom-fitted thanks to silicon injection between a hard core and a soft expandable envelope. A miniature bore in the hard core is used to determine the sound pressure level difference across the earplug and for real time monitoring of the acoustic seal during the injection process until an adequate fit has been reached.

Another benefit of this measuring capability is the development of a field method to estimate the noise attenuation obtained by such expandable earplugs as worn in the workplace. This estimation uses a statistical approach to link subjective attenuation with objective measurement of the Noise Reduction.

Further developments include inserting filtering elements in the earplug; passive filters for selective sound attenuation and active filters to let the worker hear speech and warning signals.

1. Introduction

The NIOSH (*National Institute for Occupational Safety and Health*) has gathered all its recent data and has established research needs for new Hearing Protection Devices as follow:

"[...] The noise attenuation of hearing protectors as they are worn in the occupational environment is usually quite different from that realized in the laboratory. The manufacturer's labeled NRRs [Noise Reduction Ratings] (which are currently used by OSHA [Occupational Safety and Health Administration] in determining compliance with the PEL [Protected Exposure Level] when engineering controls are being implemented or are not feasible) usually do not reflect actual experiences. Thus a pressing need exists for a laboratory method to estimate the noise attenuation obtained with hearing protectors worn in the field. Field research is now

needed to validate the new laboratory subject-fit method with onsite fit-testing methods. Research should also lead to the development of hearing protectors that eliminate troublesome barriers by providing increased comfort to wearers as well as improved speech intelligibility and audibility of warning signals [...]."

These criteria served as the guideline of the present work that deals with the development of a new earplug with increased comfort, speech intelligibility and smart custom fitting capabilities.

2. A new earplug concept

To address the comfort, speech intelligibility and individual fitting issues, a new earplug concept has been developed. This concept is based on a re-usable earplug that is instantly custom-molded thanks to thermoset silicon injection between a hard core and a soft expendable envelope. The hard core contains an inner bore that allows the temporary insertion of a miniature microphone to measure sound pressure levels in the residual ear-canal portion. Attached to the back of this internal pressure microphone, there is an external pressure microphone so that sound pressure level difference across the earplug (Noise Reduction) can be measured.

The Figure 1 below shows the expandable earplug, the mixing tip of the injection syringe, the microphone probe (external and internal pressure microphones) as well as the reference sound source.

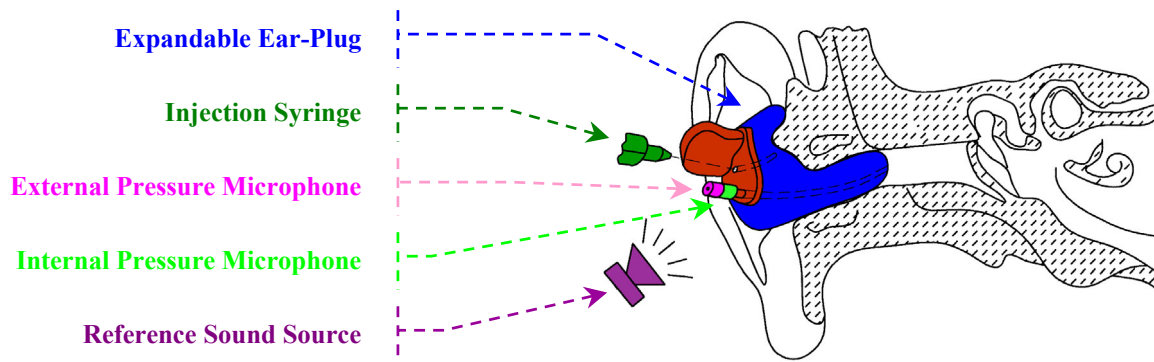


Figure 1: The new earplug concept.

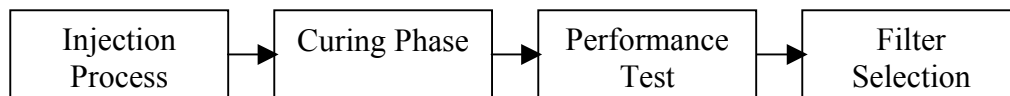


Figure 2: Steps for the production of this new earplug.

Figure 2 shows the steps required for the production of this new earplug: The earplug injection is followed by a 2½-minute curing phase, after which the user is asked to remove and replace the earplug by himself. A final measurement of the Noise Reduction (NR) is made as this time and will be used to predict what attenuation the user would experience if he were subjectively tested for attenuation. This performance test determines if the earplug deserves the

attenuation it has been officially rated for (NRR rating, for example). If the test is passed an appropriate acoustical filter will be selected and placed into the said inner bore to provide the user the exact amount of protection he needs, therefore avoiding overprotection and the associated decrease in speech intelligibility.

2.1. Injection process

The transfer function between external and internal microphone is measured in real time during the injection process. An octave band analysis from 63 to 8000 Hz is applied on the transfer function magnitude spectrum. A global indicator named "*occlusion level*" is calculated from several pertinent octave band magnitudes. When this occlusion level reaches a predetermined level (named "*Target Occlusion Level*") and stay stable for a given amount of time, the injection process is stopped.

2.2. Performance test

Once the injection material has been cured inside the earplug, the user removes and replaces the earplug by himself. Upon completion, the NR is measured again on both ears. From this measurement, two performance tests are done. The first one tests that the earplug provides the expected acoustic seal; the second one tests that the earplug deserves the NRR is has been officially rated for.

2.3. Filter selection

Once the earplug has been tested successfully, an acoustical filter can be placed into the inner bore (since the microphone probe has been removed) to let more sound get through. The filters are -at present time- pure acoustical dampers that are properly selected according to the protection outcome in Table 1 where the protected exposure level is computed from the estimated attenuation of the passive earplug and the time weighted exposure level of the subject.

Table 1: Protection outcomes at various resulting sound levels (from EN458 [1]).

Sound level resulting from the use of the protector (dBA)	Protection outcome
85 +	Insufficient
80–85	Acceptable
75–80	Optimal or Ideal
70–75	Acceptable
Less than 70	Overprotection

3. A new protection and performance evaluation approach

A field method to estimate the noise attenuation obtained by such expandable earplug as worn in the workplace has been developed. The proposed method is a MIRE method (*Microphone In the Real Ear*) that uses the Noise Reduction (*NR*) measurement on one's earplug to predict -based on a statistical approach- the corresponding subjective attenuation (*ATT*) that this user would report during a REAT (*Real-Ear Attenuation at Threshold*) test.

3.1. A statistical relationship between measured Noise Reduction and reported Attenuation

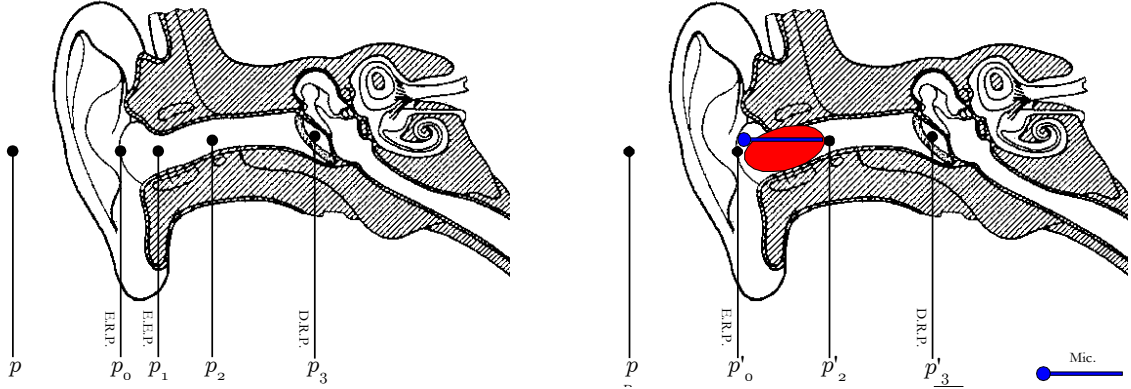


Figure 3: Transmission through unoccluded (left) and occluded (right) outer ears.

Table 2: Localization of the measurement points.

ERP	ear reference point
EEP	ear canal entrance point
DRP	ear-drum reference point

In an unoccluded ear (Figure 3, left), the Transfer Function of the Outer Ear (*TFOE*) can be determined as being:

$$TFOE = 20 \log_{10} \left(\frac{p_3}{p} \right) \quad (\text{Eq. 1})$$

In an occluded ear (Figure 3, right), the Noise Reduction (*NR*) can be determined as being:

$$NR_0 = 20 \log_{10} \left(\frac{p}{p'_3} \right) \quad (\text{Eq. 2})$$

The Insertion Loss corresponds to the difference in sound pressure level at eardrum between unoccluded and occluded conditions, it is therefore determined as:

$$IL = 20 \log_{10} \left(\frac{p_3}{p'_3} \right) \quad (\text{Eq. 3})$$

A usual relation [2] can be obtained from combining Eq. 1 to Eq. 3 together:

$$IL = NR_0 + TFOE \quad (\text{Eq. 4})$$

It has been clearly demonstrated that the Attenuation reported during a REAT measurement may be slightly overestimated (below 500 Hz) due to the masking effect -of the physiological noise (*PN*)- on occluded thresholds [1]. It remains that this reported Attenuation (*ATT*) is a subjective evaluation of the Insertion Loss (*IL*) and we can write:

$$ATT = IL + PN \quad (\text{Eq. 5})$$

From Eq. 4 and Eq. 5, we can write that:

$$ATT = NR_0 + TFOE + PN \quad (\text{Eq. 6})$$

With the setup described earlier in Figure 1, the Noise Reduction that is measured is:

$$NR = 20 \log_{10} \left(\frac{p_0'}{p_2'} \right) \quad (\text{Eq. 7})$$

Therefore, combining the previous Eq. 6 and Eq. 7, we can link the measured Noise Reduction and reported Attenuation with the following relation:

$$ATT = NR + TFOE + \underbrace{20 \log_{10} \left(\frac{p_2''}{p_2'} \right) + 20 \log_{10} \left(\frac{p_2'}{p_3'} \right) + 20 \log_{10} \left(\frac{p}{p_0'} \right) + PN}_{COMP} \quad (\text{Eq. 8})$$

- $\left(\frac{p_2''}{p_2'} \right)$ stands for the "tube effect" of the microphone probe;
- $\left(\frac{p_2'}{p_3'} \right)$ stands for another "tube effect" of the residual ear canal portion;
- $\left(\frac{p}{p_0'} \right)$ stands for the diffraction effect of the subject's head and torso.

A *compensation* term that contains all the three said corrections, the TFOE and the physiological noise masking effect can be defined. This compensation is subject sensitive and will -for a large group- distributes as a standard distribution, as we will demonstrate. Therefore, the simultaneous recording of the *NR* and the *ATT* for a large number of subjects will determine the global compensation *COMP* and the compensation per octave bands *COMPⁱ* as being respectively:

$$COMP = ATT - NR \quad (\text{Eq. 9})$$

$$COMP^i = ATT^i - NR^i \quad (\text{Eq. 10})$$

3.2. Experimental validation of the proposed statistical model

3.2.1. Experiments steps

37 tests on a group of 21 subjects aging from 20 to 56 have been conducted at ETS's research facilities to rate this new earplug according to ISO-4869 [3]. The experiment steps are the injection process (described earlier), the curing phase (which is a 2½-minute delay for injected silicon to cure) and the removal and replacement of the earplug by the subject himself (following the format given in ANSI S12.6 Method B [4]).

The data being collected is the binaural attenuation *ATT*, left ear Noise Reduction *NR_L* and right ear Noise reduction *NR_R*

3.2.2. Computation of an equivalent binaural Noise Reduction

Since the Noise Reduction has been measured on both ears (*NR_L* and *NR_R*, for left and right ear) while the attenuation *ATT* was a single binaural measure, the following formula has been used to find the resulting octave band *NRⁱ*; it take into consideration the weakest octave band Noise Reduction combined with the octave band difference in hearing threshold between both ears (*A_Lⁱ* and *A_Rⁱ*):

$$NR^i = \begin{cases} NR_L^i & \text{if } (NR_L^i + A_L^i - A_R^i) \leq (NR_R^i + A_R^i - A_L^i) \\ NR_R^i & \text{else} \end{cases} \quad (\text{Eq. 11})$$

The global Noise Reduction is computed using Eq.12.:

$$NR = 10 \log_{10} \sum_{i=1}^7 (10^{\frac{100}{10}} \div 10^{\frac{100-NR^i}{10}}) \quad (\text{Eq. 12})$$

3.2.3. Distribution of computed Compensation $COMP$

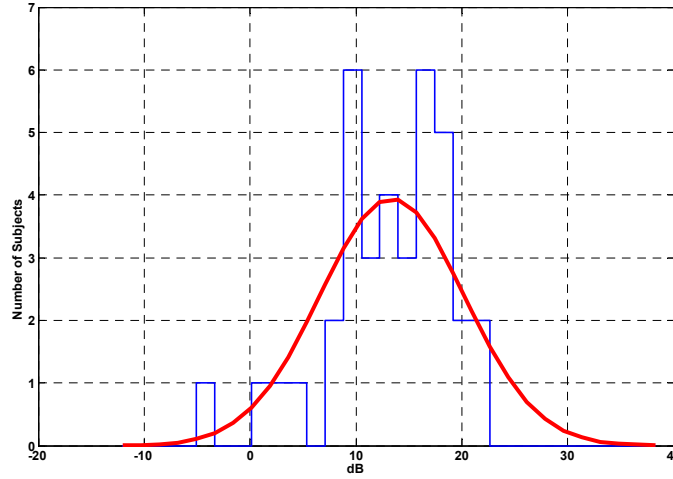


Figure 4: Discrete and continuous distribution of the global compensation $COMP$.

In a χ^2 test, according to the level of significance of $\gamma=0.05$, the difference between empirical distribution (with empirical mean value of 13.2 dB and standard deviation of 6.0 dB) and the normal distribution $\mathcal{N}(13.2, 6.8)$ is not significant. Consequently, the compensation $COMP$ can be validly adjusted to a normal distribution $\mathcal{N}(13.2, 6.8)$ [5]. The same χ^2 test for every octave band compensation $COMP^i$ shows that every $COMP^i$ can be validly adjusted to a normal distribution as given in Table 3.

Table 3: Mean value and standard deviation for octave band Attenuation ATT , octave band Noise Reduction NR and octave band Compensation $COMP$ (in dB).

	125	250	500	1000	2000	4000	8000	Global	
i	1	2	3	4	5	6	7		
$\overline{ATT^i}$	18.9	20.6	20.4	22.1	28.2	34.7	34.2	\overline{ATT}	21.4
σ_{ATT}^i	7.9	7.2	4.9	5.9	5.0	6.1	8.2	σ_{ATT}	6.0
$\overline{NR^i}$	9.1	11.2	12.7	15.8	14.0	6.5	10.6	\overline{NR}	8.4
σ_{NR}^i	6.6	6.0	5.9	4.5	2.9	5.8	5.4	σ_{NR}	3.4
$\overline{COMP^i}$	9.8	9.4	7.7	6.3	14.2	28.2	23.6	\overline{COMP}	13.2
σ_{COMP}^i	8.4	7.2	5.8	6.4	5.5	8.1	8.7	σ_{COMP}	6.8

3.3. Implementation of the performance tests

3.3.1. First test: Estimation of the global Attenuation using global compensation COMP

These first test rejects leaky earplugs. It turned out that leaky earplugs were usually badly inflated and that they don't replicate properly the user's ear shape and would cause an uncomfortable fit over the time.

The global Noise Reduction is measured for the individual pair of earplugs being tested and the global compensation calculated in Table 3 is applied using Eq. 13 :

$$\widehat{ATT} = NR_{Ind.} + COMP \quad (\text{Eq. 13})$$

As $COMP$ is defined as a normal distribution $\mathcal{N}(\overline{COMP}, \sigma_{COMP})$, the estimation of the ATT will also be distributed as a normal distribution as in Eq. 14 below.

$$\widehat{ATT} \equiv NR_{Ind.} + \mathcal{N}(\overline{COMP}, \sigma_{COMP}) \quad (\text{Eq. 14})$$

To avoid any overestimation of the ATT , a protection performance can be defined by subtracting α -times the standard deviation of $COMP$. For example, according to Table 4, for 84% protection performance, the estimated minimum ATT would be given by the equation Eq. 15 below:

$$\widehat{ATT}_{84\%} = NR_{Ind.} + \overline{COMP} - 1.00 \times \sigma_{COMP} \quad (\text{Eq. 15})$$

Table 4: Values of α for various protection performances (from [6])

Protection Performance in %	Value of α
75	0.67
80	0.84
84	1.00
85	1.04
90	1.28
95	1.64
98	2.00

The threshold of Attenuation (the critical empirical value below which no acoustic seal exists) is computed from mean and standard deviation values of ATT and a given empirical parameter α (numerically different from the previous one) using the following formula:

$$ATT_{Threshold} = \overline{ATT} - \alpha \times \sigma_{ATT} \quad (\text{Eq. 16})$$

A statistical test in Eq.13 assesses if the estimated minimum Attenuation of this earplug is above the threshold Attenuation level as determined from empirical experiments.

$$Status = \begin{cases} pass & \text{if } \widehat{ATT}_{84\%} \geq ATT_{Threshold} \\ fail & \text{else} \end{cases} \quad (\text{Eq. 17})$$

3.3.2. Second test: Estimation of the Personal Attenuation Rating using octave band compensation $COMP^i$

The Noise Reduction Rating (NRR) defined by EPA (Environmental Protection Agency) [7] can be written in this compact form below (where A_i and C_i are defined in Table 5):

$$NRR = 10 \log_{10} \sum_{i=1}^7 10^{\frac{100+C^i}{10}} - 10 \log_{10} \sum_{i=1}^7 10^{\frac{100+A^i-\overline{ATT}^i+2\sigma_{ATT}^i}{10}} - 3 \quad (\text{Eq. 18})$$

Table 5: Octave band weighting A^i and C^i .

Octave Band Frequency (Hz)	125	250	500	1000	2000	4000	8000
i	1	2	3	4	5	6	7
C^i weighting (dB)	-0.2	0	0	0	-0.2	-0.8	-3
A^i weighting (dB)	-16.1	-8.6	-3.2	0	1.2	1.0	-1.1

A Personal Attenuation Rating (PAR) (slightly modified from [8]) -that other authors named "NRR₅₀" [9]- for the individual being tested can be derived from the previous equation as:

$$PAR = 10 \log_{10} \sum_{i=1}^7 10^{\frac{100+C^i}{10}} - 10 \log_{10} \sum_{i=1}^7 10^{\frac{100+A^i-\overline{ATT}^i}{10}} \quad (\text{Eq. 19})$$

As the octave band Noise Reduction is been measured on the 125 to 8000 Hz octave bands, the octave band compensation from Table 3 can be applied using Eq. 20 to estimate the octave band Attenuation.

$$\widehat{ATT}^i = NR_{Ind.}^i + COMP^i \quad (\text{Eq. 20})$$

As $COMP^i$ are also normal distributions $\mathcal{N}(\overline{COMP}^i, \sigma_{COMP}^i)$, the estimation of ATT^i will also be a normal distribution:

$$\widehat{ATT}^i \equiv NR_{Ind.}^i + \mathcal{N}(\overline{COMP}^i, \sigma_{COMP}^i) \quad (\text{Eq. 21})$$

According to Eq. 19 and 20, the global Personal Attenuation Rating (PAR) is then computed using Eq. 22:

$$\widehat{PAR} = 10 \log_{10} \sum_{i=1}^7 10^{\frac{100+C^i}{10}} - 10 \log_{10} \sum_{i=1}^7 10^{\frac{100+A^i-\widehat{ATT}^i}{10}} \quad (\text{Eq. 22})$$

To avoid any overestimation of the PAR , a protection performance can be defined by subtracting α -times the standard deviation of $COMP$. As previously, for a 84% protection performance (refer to Table 4), the minimum estimated PAR would be:

$$\widehat{PAR}_{84\%} = 10 \log_{10} \sum_{i=1}^7 10^{\frac{100+C^i}{10}} - 10 \log_{10} \sum_{i=1}^7 10^{\frac{100+A^i-(NR_{Ind.}^i+\overline{COMP}^i)+1.00 \times \sigma_{COMP}^i}{10}} \quad (\text{Eq. 23})$$

$$Status = \begin{cases} \text{pass} & \text{if } \widehat{PAR}_{84\%} \geq NRR \\ \text{fail} & \text{else} \end{cases} \quad (\text{Eq. 24})$$

4. Conclusion

A new earplug concept that addresses most of the concern of today's HPD has been presented:

- For superior comfort, the earplug is instantly custom-molded into the user ear by the injection of medical grade silicon into an expandable envelope,
- For onsite fit-testing, the Noise Reduction of the earplug can be easily measured; two performance tests have been proposed for checking the protection and the comfort provided.
- For speech intelligibility, the earplug is filtered to provide the user the exact amount of protection he needs also avoiding the risk of over/under protection.

Future work will include an updated statistical model with official data from ANSI S3.14 and S12.6 tests; an analytical modelisation of the propagation through the outer ear to compute precisely the basic sound transmission relationship in any particular ear; the development of moderated uniform attenuation filters and active-filtering approaches for voice enhancement.

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