THE PARVUM BONUM, PLUS MELIUS FALLACY IN EARPLUG SELECTION.

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Outline:

I. Why musicians need moderate-attenuation high-fidelity earplugs.

II. Why most workers need moderate-attenuation hearing protectors.

III. Almost no one needs the earplugs we've been selling! And now (God only knows why), the common market has outlawed the moderate-attenuation earplugs that most people need.

IV. The Allen-Berger Solution, the Carlson solution, and other happier matters.

I. Why musicians need moderate-attenuation high-fidelity earplugs.

The humorous drawing in Figure 1 illustrates a practical reality: Virtuoso musicians must practice all the time. The violinist Isaac Stern was once reported to have said, "If I don't practice for a day, I know it. If I don't practice for two days the orchestra knows it. If I don't practice for three days, everyone knows it!"

As an amateur violinist, I know only too well the repetition, repetition, repetition required of a difficult passage. Unfortunately, it is precisely the high-intensity passages which require the most practice. Those are the passages where the violinist is pushing the fiddle to the limit; any more pressure and the tone breaks up into a raucous screech, any less and the excitement of the passage - of playing out over the entire orchestra - is lost.

I am going to play a recording made from deep in the left earcanal of Ruben Gonzalez, co-concertmaster of the Chicago Symphony, rehearsing one such passage from the Brahms Violin Concerto in D (the triple-stop passage starting at bar 246, a passage I dearly wish I could play).


"Maybe you should start smoking again."

Fig. 1
A musician must practice, practice, practice.

The recording was made with a flat-frequency-response probe microphone which was then diffuse-field-inverse (DFI) equalized to remove the resonance of Mr. Gonzalez's earcanal so that you can use your own when you listen. The violin that Mr. Gonzalez plays these days is a very powerful Bergonzi that last belonged to Itzaac Pearlman, and to Fritz Kristler prior to that. I will not play that recording at its original level - which had A-weighted peaks of 112 dB SPL after DFI equalization - but at a level that will be 5-10 dB lower, depending on your location in this room. (The recording was played for the attendees. Nearly everyone winced in pain.)

Not surprisingly, perhaps, Mr. Gonzalez (who has kindly given permission for his case to be discussed and his audiogram to be shown) has a 55 dB "music-induced notch" in his left-ear audiogram at 3 & 4 kHz, as shown in Figure 2. Mr. Gonzalez's right ear (shielded from the violin by his head) shows normal hearing.

In a study of the music-performance risks for the Chicago Symphony Orchestra, Julie and Larry Royster and I placed dosimeters on several dozen CSO players for rehearsal, concert, and - in the case of Ruben Gonzalez -- practice at home (Royster et al, 1991). In Mr. Gonzalez's case, we obtained a total of 11.5 hours of dosimeter readings on four different days, days which included a (non-soloist) concert performance, a rehearsal, and several hours of intense practice. The 8 hour LEQ calculated from those 11.5 hours of recordings, taking into account the 60-plus hours a week he has a violin under his chin, was 105 dB. The 8 hour LEQ is the steady-state sound Level which, if applied continuously for 8 hours, would produce the calculated damage risk equivalent to the integration of the varying exposure actually experienced.

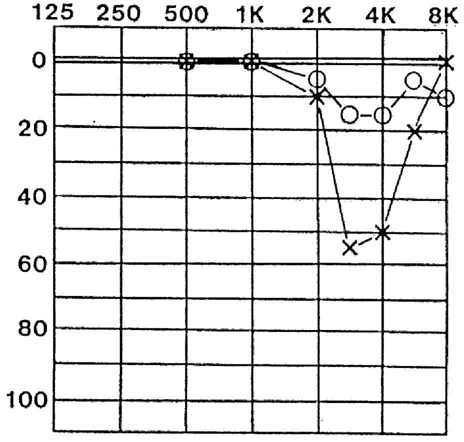
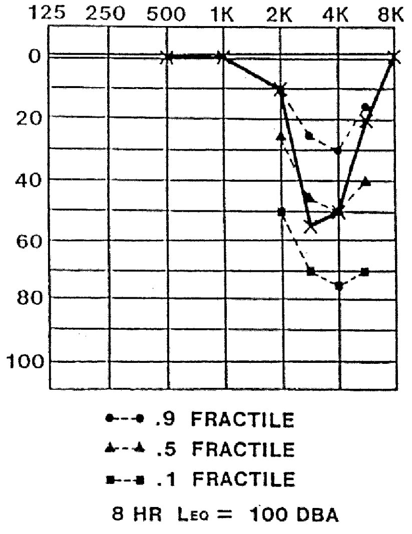


Fig. 2
Audiogram of a virtuoso violinist after 30-35 years of high-intensity playing (45 years total).

The bottom half of figure 3 shows the calculated .1, .5, and .9 fractile curves for expected hearing loss from 105 dBA LEQ exposure for the 30 years that Mr. Gonzalez has been a virtuoso, soloing with major orchestras around the world. His actual loss is less that the 50-percentile curve, indicating that either his ears are a little less susceptible than average or his actual exposure over those 30 years averaged less than 105 dB. The latter explanation has some support from the fact that Mr. Gonzalez was intensely practicing the Brahms violin concerto during the period where dosimeter readings were being made. The top half of figure 3 shows the expected hearing loss for 100 dBA LEQ for 30 years. The 50%-tile curve matches Mr. Gonzalez' left-ear audiogram quite nicely.



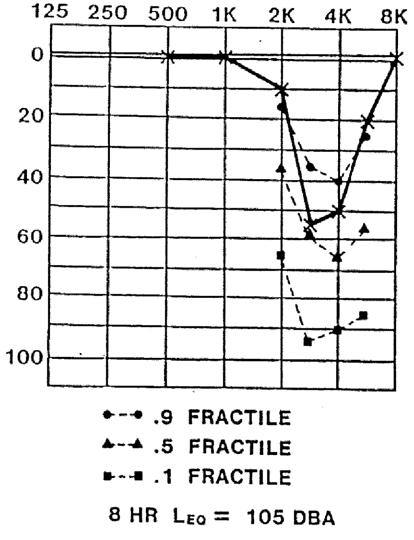


Fig. 3
Comparison of measured virtuoso violinist left-ear audiogram to predicted NIPTS (noise induced permanent threshold shift). Based on 30 years of 40 hour/week exposure and 8 hour LEQs calculated from 11.5 hours of dosimeter measurements.

Figure 4 shows the summary of the results for the males in the Chicago Symphony study. Note that the average age-corrected male (if such a thing is possible) has, at all frequencies, better hearing than the average non-industrial-noise-exposed "man on the street" male, but clearly shows a slight "4 kHz notch" and does not equal the hearing levels of the pristine, medically and audiologically screened, ISO population until 8 kHz is reached. Flute players had statistically significantly greater loss in their right (flute-side) ears than left ears; violin players had significantly greater loss in their left (violin side) ears. There is no longer any doubt in my mind that even orchestra musicians are at risk, slight but real, of hearing damage due to their playing.

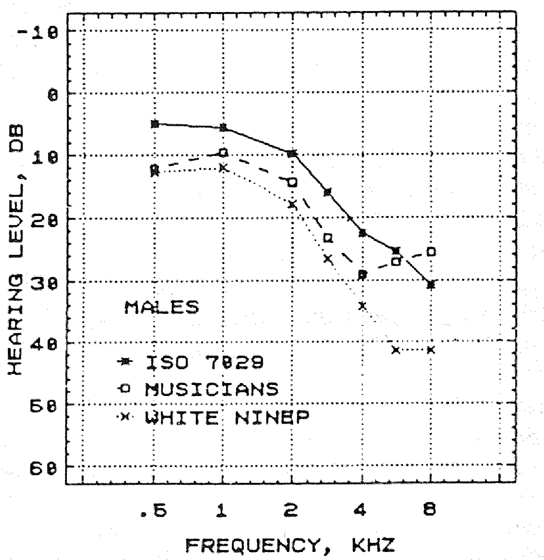


Fig. 4
Age-matched thresholds from Chicago Symphony Orchestra study (used with permission from Royster et al, 1991)

The principal risk, incidentally, appears to come not during performance but during the time spent practicing and -- for those orchestra members who "moonlight" in jazz bands -- off-symphony exposures. Moonlighting may be great for the "chops," but it can add significantly to the total exposure.

Why don't musicians use the yellow foam earplugs, which provide the highest measured attenuation of any earplug in the world? The obvious answer is that musicians need to hear while they play (Altshuler, 1989; Van Horn, 1991). They need a little attenuation to protect their hearing for the future, but a lot of attenuation would risk their jobs in the present!

II. Why most workers need moderate-attenuation hearing protectors.

Some workers obviously need high-attenuation earplugs. Shipbuilders, flight crew who stand behind jet aircraft on the flight deck, and army-tank operators usually fall in this category. Such individuals often can't get enough attenuation for proper protection even with plugs and earmuffs combined.

The majority of workers, however, fall in a different category. Although some 1/3 of all factory workers require hearing protection in the U.S., based on the rule that anyone exposed to more than 85 dB 8-hour TWA (total weighted average) for 5 days per week needs hearing protection, 76 percent of those workers need less than 10 dB of protection. In other words, 76 percent of the workers who need hearing protection are exposed to less than a 95 dB 8-hour TWA (Royster, 1993).

It seems more than likely that similar findings hold in Europe. These facts bring us to the conclusion that:

III. Almost no one needs the earplugs we've been selling! And now (God only knows why) the common market has outlawed the moderate attenuation earplugs that most people need.

For some time, I have enjoyed taking swipes at the "More Is Better" line of thinking. Following the dictum that any self-respecting fallacy should be in Latin ("Post Hoc, Ergo Propter Hoc" comes to mind), I asked my Latin-teacher-and-scholar sister for a Latin version of the fallacy in reasoning that has been driving our hearing protection thinking. Figure 5 is her contribution to clearer thinking in our industry (Hellenga, 1990). The fallacy, Parvum Bonum, Plus Melius (Par-woom Bow-num, Ploose Mel-ee-oose [oo as in moose]), is the old "More Is Better" fallacy in fancy clothes.

THE PBPM FALLACY:

"PARVUM BONUM, PLUS MELIUS"

(A LITTLE IS GOOD; MORE IS BETTER)

Fig. 5
The basis of the popularity of excessive-attenuation hearing protectors.

Both the design and sales of most earplugs in the United States has been driven by the PBPM, More is better, fallacy. "The best NRR wins," says the marketing department.

In the Common Market, earplugs whose average attenuation is slightly greater than that needed by the vast majority of workers cannot be sold as earplugs. By the time the standard deviation of the test method is factored into account, a true 15 dB attenuation earplug (i.e., one which produces a mean 15 dB attenuation at all frequencies) produces a rated attenuation below the 12 dB minimum required above 500 Hz by the new standard. The sad irony is that even 12 dB is more than the majority of workers require. An earplug that gave an actual attenuation of 8 dB - about right for most workers - would probably give an NRR of -1 dB and couldn't be sold even in the U.S.

The thing wrong with the More Is Better fallacy is that it is simply wrong. If two Aspirin are good for a headache, you should take the whole bottle? If studies show that mild exercise, 2-3 miles per day, is good for you, running 100 miles a day would be better? If medical research shows that those who have a couple of drinks a day have fewer heart attacks, shouldn't we drink a whole bottle every day? These examples are so silly that I'm embarrassed to use them, but they are no more silly than the reasoning behind most hearing protectors.

Who would buy sunglasses so dark that you couldn't see the cars coming down the road? No one. Who would buy earplugs so effective that you couldn't hear a fork lift truck coming up behind you or a distant shouted warning? Everyone; at least every industrial buyer. We've trained them.

If we used as much vigor protecting the present hearing of workers in their working environment as we do trying to protect their future hearing, I believe earplugs would carry two ratings: Something like a) the NRR (Noise Reduction Rating), which (simplified) equals the average attenuation minus two standard deviations of the measured data minus a 3 dB safety factor, and b) what I've proposed[1] as the ARR (Audibility Reduction Rating). The ARR would equal the average attenuation plus two standard deviations of the measured data plus a 3 dB safety factor.

Figure 6 illustrates the application of the suggested improvement to the U.S. rating system, using the popular yellow slow-recovery-foam E-A-R earplugs as an example. Properly inserted, they have an across-frequency average attenuation of 40 dB, giving an NRR of 29 dB (the rated value) and an ARR of 51 dB. Someone with 25 dB hearing level -- on the "normal" fence -- would have a worst-case 76 dB hearing level wearing these plugs: he or she would be rated severely impaired. Someone with a 39 dB hearing level would be rated -- in the calculated worst case -- as profoundly hearing impaired wearing those earplugs.

THE OLD STUFF:

NOISE REDUCTION RATING:

N.R.R. = AVG ATTEN − 2 SIGMA − 3 DB

A NEW PROPOSAL:

AUDIBILITY REDUCTION RATING

A.R.R. = AVG ATTEN + 2 SIGMA + 3 DB

AN EXAMPLE: N.R.R. - 29 DB
A.R.R. = 51 DB

(WITH 25 DB HEARING LOSS, 76 DB HL: "SEVERE HL")

Fig. 6
Suggested addition to the U.S. NRR rating scheme to provide a more nearly balanced set of information to users and purchasers of hearing protection.

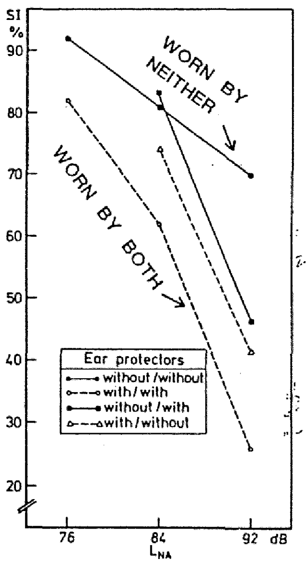


Fig. 7
Effect of ear protectors worn by talker and/or listener (used with permission from Hormann et al, 1984).

The lost audibility and it's effects are not simply computational constructs. The damage that excessive-attenuation hearing protectors do to their wearer's ability to hear effectively in typical noise environments is shown in Figure 7 (from Hormann et al; 1984). Note that if either the talker or the listener wears excessive protection the ability to communicate drops dramatically. When both wear protection, the SI (Speech Intelligibility Index) drops to 25% in 92 dB SPL noise.

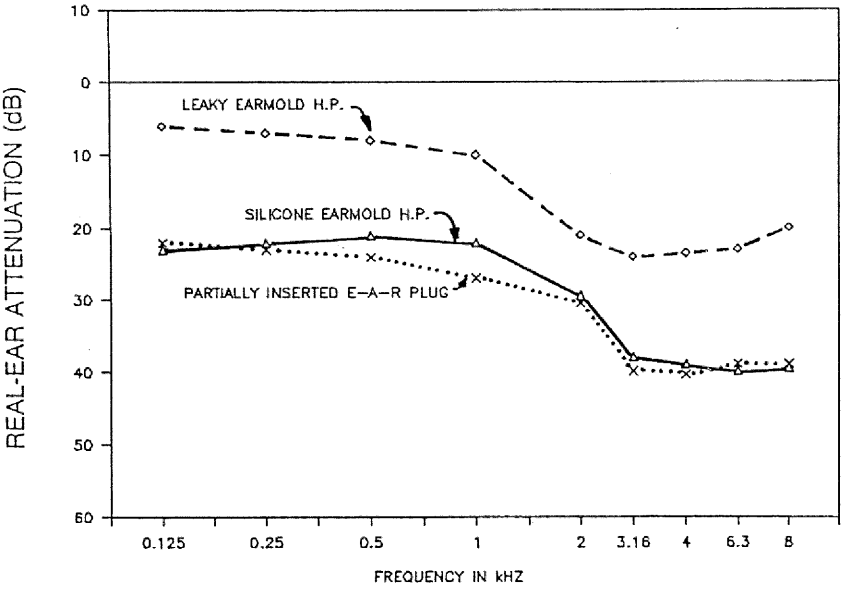
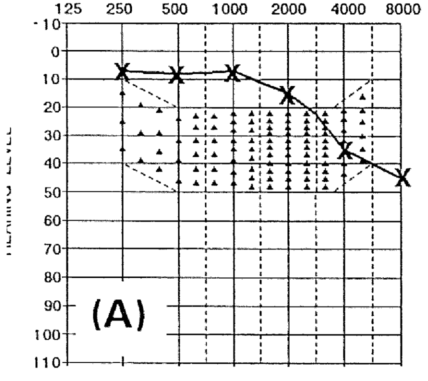


Fig. 8
Attenuation of representative earplugs.

There is another, more subtle difficulty with most hearing protectors: they provide 15 to 20 dB greater attenuation for high frequencies than for low frequencies, as shown in Figure 8. In other words, they muffle the sound. The problem is that many if not most workers in jobs requiring hearing protection already have some noise-induced high-frequency hearing loss. And even without obvious noise-induced hearing loss, muffled highs can cause a problem for older workers.

Figure 9 illustrates the consequences of a mild hearing loss when combined with the excessive high-frequency attenuation of typical hearing protectors. The mild loss shown in Figure 9A is taken from the published hearing levels for a typical 50-year old male (which is not so old, after all!). Figure 9B shows the resulting hearing levels if that individual uses the partially-inserted E-A-R foam plug with the attenuation shown in Figure 8 (taken from data obtained by E. H. Berger; 1990). Such an individual has a calculated A.I. of only 0.31, i.e., hears only 31% of the important speech cues (Mueller & Killion, 1990). When that individual goes from the work area into the office, or on coffee break, or for lunch, he or she must remove the plugs to hear. Then replace them out in the work area. Then remove them...then replace them...then remove them...then replace them...then...,in and out several times a day.



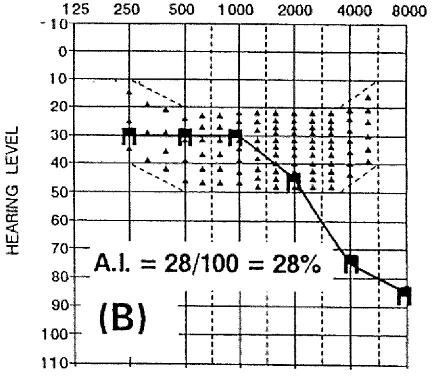


Fig. 9
Mild hearing loss of typical 50 year old male (A), and moderate-severe "hearing loss" he must accept while wearing typical earplugs (B).

We can imagine why such a person gets tired of the bother, and figures out a better compromise. That is exactly how I interpret the data of Figure 10 (Berger, 1983), which shows that earplugs with a laboratory NRR of 20 to 30 dB are worn in the field in such a way that the measured NRR drops to 2 to 10 dB. It has sometimes been argued that Figure 10 shows workers are too stupid or too poorly instructed to wear their hearing protectors properly. I argue that it shows how intelligent workers are: when presented with excessive-attenuation earmuffs they drill holes in them so they can hear; when presented with excessive-attenuation earplugs they turn them sideways and place them in the concha where they are highly visible (see, sir, they're all wearing their earplugs!) but don't interfere with hearing.

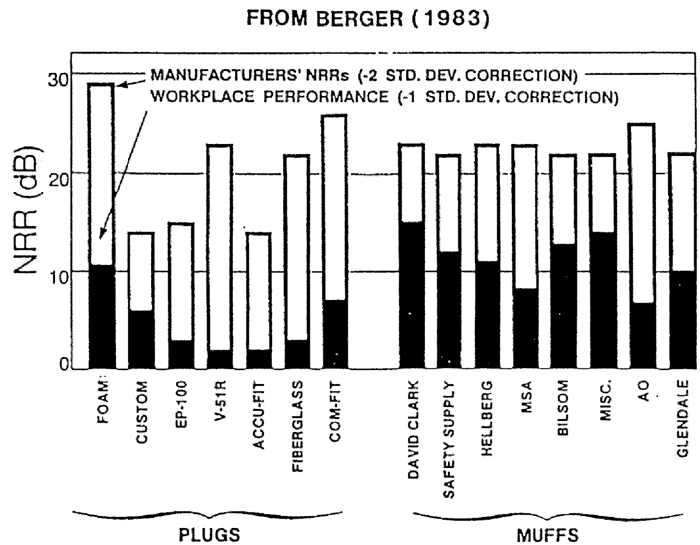


Fig. 10
Difference between real-world and laboratory rating of hearing protectors.

My favorite visual illustration of our standard approach to hearing protector design is a color slide which says "WHO WANTS EARPLUGS THAT WON'T LET YOU HEAR." In this slide[2], the top half of each of the letters is colored blue, the middle half is colored green, and the bottom half is colored red. When the visual equivalent of muffle-the-highs, excessive-attenuation earplugs (dark red sunglasses) is placed in front of the projector, only the lower red third of each letter can be dimly seen. If you purchased sunglasses as we purchase hearing protection, you would be able to see only the red cars coming at you down the road: the blue and green cars would be too dark to see.

IV. The Allen-Berger Solution, the Carlson solution, and other happier matters.

Fortunately, improved hearing protection devices are available. The first was a new earmuff design (Allen and Berger, 1988) which E-A-R corporation manufacturers as the E-A-R 9000 model. It produces a nearly uniform 25 dB attenuation across the audiometric frequencies and produces an NRR of 16 dB. An attenuation of 25 dB is still a bit high for most workers, who need only 8-10 dB, but it was the first of its kind and had to contend with a skeptical marketing department who believed, of course, that More Is Better and that an NRR of only 16 dB was asking for trouble in the marketplace.

Whatever its limitations in marketing courage, the E-A-R 9000 earmuff is much better than any other earmuff with which I'm familiar for the typical worker. Especially important is the fact that it circumvents the muffled-highs problem of traditional earmuffs by use of a special high-frequency sound channel to bring the highs into the concha.

The solution I want to talk mostly about, however, is not an earmuff but a high-fidelity earplug; one so small it becomes almost invisible in the ear. This earplug is called the model ER-15 "musicians earplug," reflecting the fact that many well-known classical and rock musicians are now using it, but it might just as well have been called the "Carlson earplug" - after Elmer Carlson who developed it - except that Carlson declined the honor.

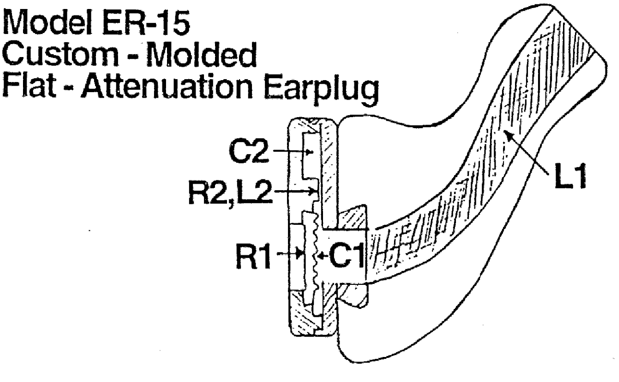


Fig. 11
Construction and equivalent-acoustical-circuit elements of ER-15 Musicians Earplug^{TM} *designed by Carlson.*

Figure 11 shows the construction of the musicians earplug. In order to provide 15 dB attenuation at low frequencies, Carlson incorporated a plastic diaphragm whose compliance was approximately one-fourth the compliance of the earcanal and eardrum, producing a slightly more than 5:1 reduction in pressure at low frequencies. In order to replicate the natural frequency response of the open ear, which has approximately a 15 dB boost in eardrum pressure at 2.7 kHz, Carlson used the acoustic mass of the sound channel to resonate with the total compliance at 2.7 kHz. The proper value of cloth damping resistance tames the resonance peak and produces the required 15 dB boost at 2.7 kHz. The compliance and resistance are built into the earplug "button" and tested for proper value at the manufacturer (Etymotic Research). The acoustic mass in the sound channel is under the control of the earmold laboratory. Because of the near impossibility of controlling the acoustic mass by dimensional control in a tortuous sound channel, an acoustic mass meter is supplied to the earmold manufacturers so they can measure the actual acoustic mass after each successive boring operation.

Figure 12 shows the diffuse-field response of the average open ear, represented by the KEMAR manikin in this case, and the diffuse-field response of the same ear with an ER-15 musicians earplug in place. Note that at each frequency there is a nearly exact 15 dB reduction in eardrum pressure with the ER-15 in place.

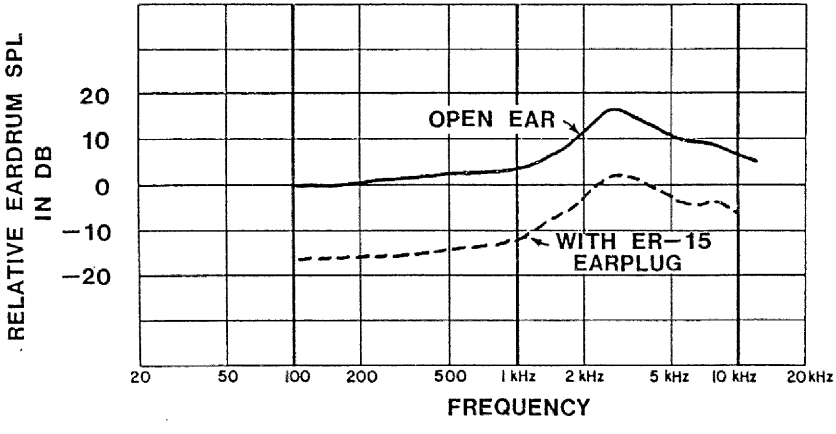


Fig. 12
Expected eardrum SPL in diffuse (random incidence) sound field with ear open or occluded with Musicians Earplug.

Figure 13 shows the measured real ear attenuation at threshold (REAT) for the ER-15 and more common earplugs, measured on human ears in a standardized diffuse-field testing facility (Berger and Lindgren, 1992). Gratifyingly enough, similar data were obtained recently by A.M. Mimpen of the TNO on ER-15 earmolds manufactured by ELCEA. Figure 13 illustrates the improvement in a) attenuation (less) and b) high frequency response (much improved) brought about by Carlson's invention.

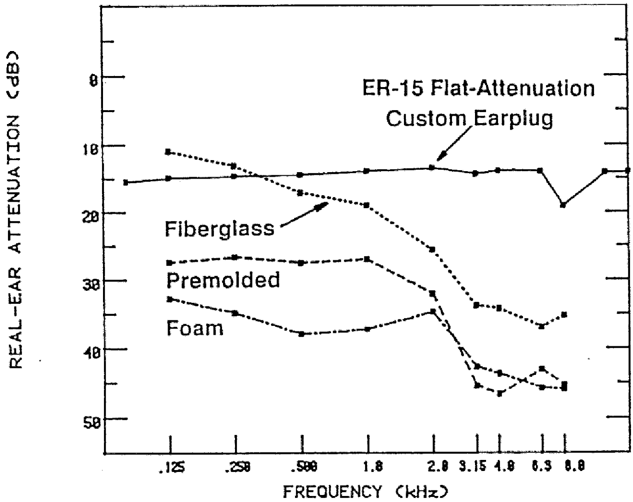


Fig. 13
Comparison of ER-15 earplug with traditional earplugs.

The principal disadvantages to the musician's earplug were:

a) delivered cost, typically $120-130 U.S. dollars including the custom impression, the earmolds, and the attenuator buttons;

b) insufficient attenuation for many "heavy metal" hard rock musicians, who liked the greatly improved clarity of sound but found they were still insufficiently protected by 15 dB of attenuation.

Briefly, two additional products have been introduced to answer the needs stated in the last paragraph.

Figure 14 shows the construction of a one-size-fits-most ready-to-wear earplug (Killion et al, 1992). This earplug is called the model ER-20 "High Fidelity" earplug, reflecting the fact that it has excellent fidelity compared to common earplugs, but it might just as well have been called the "everymans earplug" -- reflecting the attempt to design an earplug that everyone could afford -- except that we didn't think of it soon enough. The present retail price is about 20 U.S. dollars. The mutual goal of Etymotic Research and the Cabot Safety Corporation (the joint developers of the final production version) is to reduce the cost sufficiently to permit high-fidelity earplugs to be dispensed for $10.00 each alongside beer, popcorn, and sunglasses at rock concerts and hockey games.

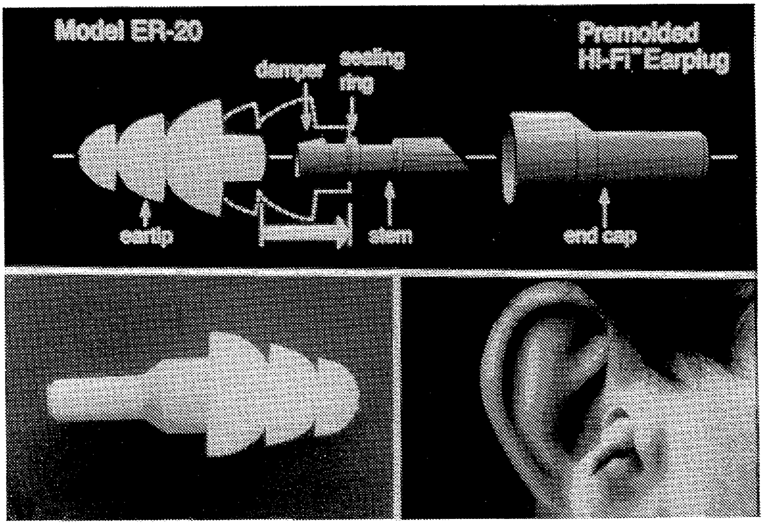


Fig. 14
Construction of ER-20 Hi-FiTM earplug.

Figure 15 shows the measured REAT attenuation of the ER-20 High-Fidelity earplug. The attenuation of the ER-20 was intentionally increased to an average value of 20 dB because - you guessed it - the marketing people were afraid that any earplug with an NRR less than 11 dB could not be sold. Fortunately, most (though not all) listeners can accommodate 20 dB of attenuation and still hear reasonably well, so it may have been a wise initial choice. The measured NRR of the ER-20 is 12 dB.

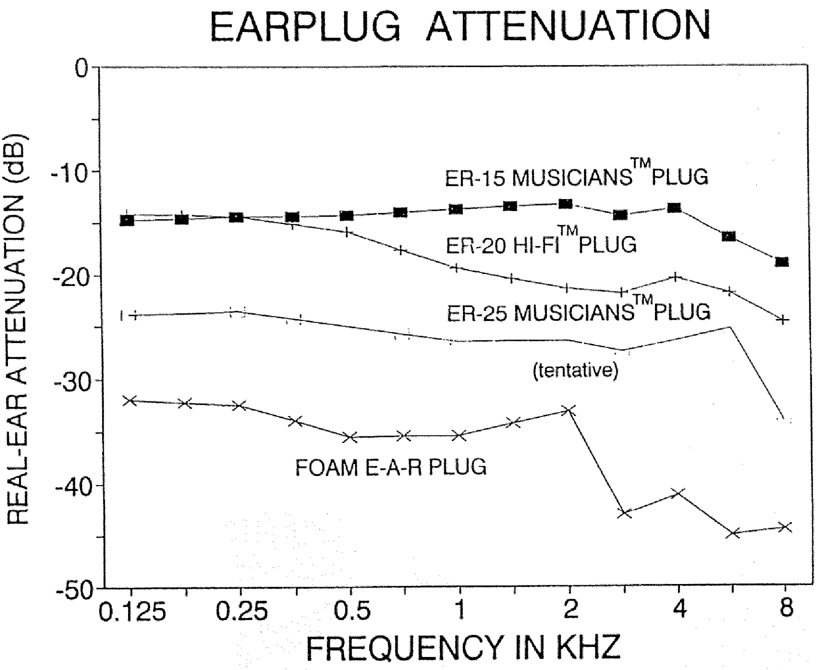


Fig. 15
Attenuation of three uniform-attenuation earplugs and one foam earplug.

Literally in response to requests, we designed a 25-dB version of the original 15-dB attenuation ER-15 button[3]. To distinguish the two without visible marking on the audience side, we kept the black color for the snap-in collars on the ER-15 buttons, and used white collars on the ER-25 buttons. We would have used red collars for the ER-25, but the cost of a special-color 250 kilograms lot of plastic seemed hard to justify. My other suggestion, metallic-color buttons for "heavy metal" bands, was likewise discarded by my associates for reasons I never fully understood.

Figure 15 shows the measured REAT attenuation for all three moderate-attenuation earplugs discussed here, along with the published attenuation for a standard-inserted foam E-A-R plug (Berger, 1990).

Finally, Figure 16 shows an electronic approach to hearing protection. By use of well-sealed earmolds and the K-AMP hearing aid circuit wired for hearing-protection applications, it is possible to provide 12 dB of attenuation for sounds in the 90-110 dB SPL region, while automatically providing 13 dB of gain for quiet sounds (below 40 dB SPL). For the worker or musician who already has a hearing loss, this arrangement makes it possible to wear a hearing protector which acts as a hearing aid for quiet sounds. Unlike many previous hearing aid circuits, whose inputs would overload once noise levels exceeded 90 dB, the ability of the this circuit to operate undistorted for inputs up to 110-115 dB SPL makes it well suited for hearing protection applications.

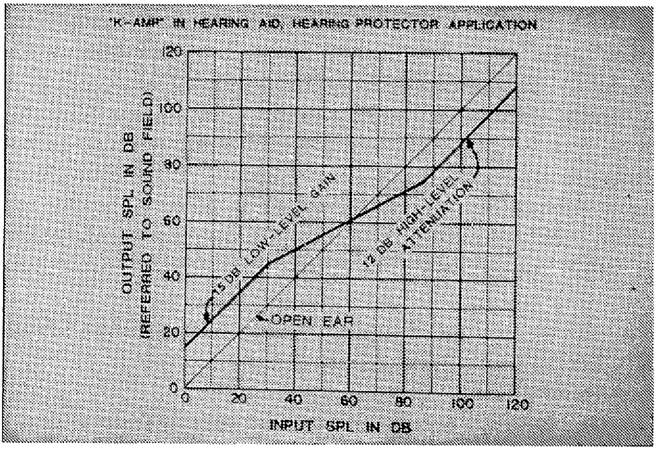


Fig. 16
Electronic earplug with low distortion in 90-115 dB SPL noise and mild gain in quiet

If I may close with a personal note: I and many friends have found that carrying a pair of musicians earplug in our pockets has dramatically increased our enjoyment of airplane trips, sporting events, music events, and even driving on long trips. We arrive less fatigued, and we can still enjoy a comfortable conversation with our seatmates. The world is a noisy place. Even when your hearing is not at risk, it is often nice to be able to turn down the volume a bit!

ACKNOWLEDGEMENTS

The author is indebted to many teachers in this field. Suspecting that none of them would entirely approve of the opinions expressed here, he nonetheless acknowledges with gratitude their attempts to instruct him. He is particularly indebted to Elliott Berger, who has provided a wealth of scientific information, instruction, and wisdom over the years.

FOOTNOTES

1. In this written version I took out my verbal comments about "repeatedly proposed" and "no one pays any attention to me" because they only expressed the childish irritation of a presumed adult. The problem sorely needs someone to make a move other than smile graciously, however, because people are losing their hearing because they refuse to wear their assigned hearing protectors because those protectors provide excessive attenuation because our More Is Better approach to hearing protection mandates excessive attenuation. Right now, all the regulatory energy in Europe appears to be headed in exactly the wrong direction.

2 Anyone wishing a personal copy of this multi-color EARPLUGS THAT WON'T LET YOU HEAR slide may drop the author a note. A copy will be sent reasonably promptly at no charge.

3 The on-stage levels produced by some rock groups in front of their individual monitor speakers are almost beyond belief. I hear the numbers and forget them because I don't have any storage location in my head for such large numbers. I know from experience, however, that levels of 100-105 dB are not uncommon at the piano player's head in more conventional partially-amplified jazz orchestras. One rock drummer told me that after <u>one set</u> listening to a misadjusted (too loud) horn driver near his right ear, his hearing in that ear was completely gone (forever).

REFERENCES

Allen CH and Berger EH (1988).
Development of a unique passive hearing protector with level-dependent and flat attenuation characteristics. NCEF 34(3) 97-105.

Altschuler M (1989).
Balanced attenuation ear protection. Sound & Comm. 35(3) 12-14.

Berger EH (1983).
Using the NRR to estimate the real world performance of hearing protectors. Sound and Vib 17(1) 12-18.

Berger EH (1990).
Personal communications.

Berger EH, and Lindgren F (1992).
Current issues in hearing protection. In Noise-Induced Hearing Loss edited by AL Dancer, D Henderson, RJ Salvi, and RP Hamernik. (Mosby-Year Book, Inc.; St Louis, MO) 377-388.

Hellenga V (1990).
Latin version of "More is Better." Personal communication.

Hormann H, Lazarus-Mainka G, Schubeius M, and Lazarus H (1984).
The effect of Noise and the Wearing of Ear Protectors on Verbal Communication. Noise Control Eng J 23(2): 69-77, and (1984).

Killion MC, Stewart JK, Falco R, and Berger EH (1992).
Improved audibility earplug. U.S. Patent 5,113,967.

Mueller H and Killion MC (1990).
An easy method for calculating the articulation index.
Hearing J 43(9) 14-17.

Royster JD, Royster LH, and Killion MC (1991).
Sound Exposures and hearing thresholds of symphoy orchestra musicians. J Acoust Soc Am 89 2793-2803.

Royster LH (1993).
Personal communication regarding data from Department of Labor Occupational Safety and Health Administration, Occupational Noise Exposure Hearing Conservation Amendment, Part III. U.S. Federal Register, Friday Jan 16, 1981, pp4078-4179.

Van Horn R (1991).
Westone hearing protection devices. Modern Drummer June 43-44