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## Improved Measurement of Leakage Effects for Circum-aural and Supra-aural Headphones

Todd Welti

Harman International Inc. Northridge CA, 91360, USA  
[todd.welti@harman.com](mailto:todd.welti@harman.com)

### ABSTRACT

Headphone leakage effects can have a profound effect on low frequency performance of headphones. A large survey, including over 2000 individual headphone measurements, was undertaken in order to compare leakage effects on human test subjects to leakage effects of the same headphones measured on a test fixture. Ten different commercially available headphones were used, each measured on eight different test subjects and a test fixture with several sets of pinnae. Modifications to the pinnae were investigated to see if the leakage effects measured on the test fixture could be made to better match the real world leakage effects measured on human test subjects.

### 1. INTRODUCTION

Headphone leakage effects can have a profound effect on low frequency performance of headphones. Deviations of 20 dB or more in the headphone response can easily result from varying amounts of leakage. The effect of a leak on a closed cavity is technically well understood [1]. Even so, for many headphone designs, leakage is still the largest source of variability in perceived low frequency response. Reducing this variability would be the best solution for this problem, and various strategies have been used to minimize the variation. Given that the variation cannot be entirely eliminated, a measurement method that approximates the average response on the headphones on human subjects would be advantageous. This is the focus of the current investigation.

Some previous related studies have been made comparing different pinna sets, such as in [2]. In this study different pinnae were considered, as well as different pinna hardness, but the focus was on reproducibility of measurements. There were no measurements made on human test subjects for comparison to the artificial pinna.

The current study includes a large number of measurements, directly comparing several pinna versions to measurements on human subjects. It includes a sizeable sampling of headphones and test subjects, including over 2000 individual measurements in all.

### 1.1. Real World Leakage effects

The fundamental mechanism for leakage effects in headphones is relatively simple and readily understood [3, 4 pp. 494-496]. The headphone cups create a closed volume when placed on the head. The acoustical source (driver) and receiver (ear drum) are both included in this volume. In most cases, there will also be some leakage. In some cases the leakage area is so large as to effectively swamp out the effects of the closed volume. An extreme example would be the extra-aural<sup>1</sup> headphone, which does not even attempt to enclose the pinna. In-ear headphones also involve a (much smaller) closed volume and potentially larger leakage effects, but are not considered here.

Leakage itself can be caused by incomplete seal of the headphone cushion on or around the pinnae. Leakage can also be an integral part of the headphone design. So-called “open back” headphones do not include an acoustically impermeable barrier behind the driver, and thus have a large leakage component. Note that some additional leakage effects can still be seen in these headphones due to imperfect and variable seal on human heads. Leakage can also be purposely incorporated in headphone design, the controlled leakage minimizing the effects of the uncontrolled leakage [4, pp. 501-502].

Leakage effects are very difficult to fix using any type of fixed electrical filter. If the headphone has poor fitment and high leakage then it often can have highly variable low-frequency response for even a single user. In other words, the response is not consistent as the user moves them around on their head, or from user to user.

The leakage effects caused by an incomplete seal of the cushions to the head can be particularly difficult to account for. Differences in head shape/size, pinna size etc. can interact with the headphone yoke and cushion mechanical design in a complex manner. Commonly used measurement techniques are not well suited to measuring real world leakage. Some methods which use a flat plate or conical shaped fixture [5], attempt to eliminate all leakage in the interests of repeatability. This works best for headphones with little or no inherent leakage, but will over-represent bass output for many other headphones. Another approach is to introduce a fixed leakage, representing an “average” effect for all

headphones measured [4, pp. 564-565]. This will give incorrect measurements for headphones with more or less leakage than the average leakage assumed. While both of these methods do not accurately capture leakage effects, they are generally repeatable, leading to their continued use.

### 1.2. Goal

In the current investigation, a large number of measurements (over 2000 in all) were made using ten different headphones on eight different test subjects, as well as on a test fixture using several different measurement methods. The main goal was to *compare measurement results from various test setups to measurements made on real ears, and look at ways to improve the accuracy of the coupler method with respect to leakage effects*. The measurement method that most accurately predicts how the headphones measure on real people was considered to be the best method.

Though measurements were made full bandwidth, the focus was only on leakage effects, which occur generally below 1 kHz. In fact, analysis at higher frequencies using this data is difficult due to the fact that the reference point for coupler (ear drum) and the test subjects (blocked canal), is different. This has minimal effect at low frequencies but would have a large effect at high frequencies.

Analysis of the data in this investigation focused on correlation between test fixture measurements and real world headphone measurements on humans, and possible improvements. The main focus was on pinna shape and physical properties.

## 2. METHOD

### 2.1. Headphones

Originally, five headphones were selected and tested. Subsequently, another five were added to the study, for a total of ten. Some headphones were chosen due to prior use of them for virtual headphone tests [6] (K550 and K701), and some were chosen due to their known leakage issues. One noise-cancelling headphone was included. Closed headphones were emphasized due to expected leakage issues. Table 1 shows the headphones used.

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<sup>1</sup> Extra-aural headphones do not touch the head or pinna at all.

Table 1 Headphones used in this study.

Headphone model	Type	Notes
AKG K701	Circumaural, open	Used for virtual headphone tests
AKG K550	Circumaural, closed	Possible leakage issues
B&W P5	Supra-aural, closed	Rectangular form factor, unusual fitment
Bose AE2	Circumaural, closed	Smallish cup barely covers ear
Beats Executive	Circumaural, closed, NC	Noise cancelling
Sennheiser HD518	Circumaural, open	Used for virtual headphone tests
AKG K545	Circumaural, closed	Possible leakage issues
AKG K619	Supra-aural, closed	Small round cups (typical form factor)
Sennheiser Momentum	Circumaural, closed	Small oval cups
Sennheiser HD800	Circumaural open	Very large and irregular shaped cups

minimize any uncertainty due to microphone responses and low frequency acoustical noise. Each subject was fitted with their own set of microphones to be used for all subsequent tests (Figure 1). Each headphone was measured at the blocked canal of each subject 6-8 times, over two measurement sessions on separate days. Subjects removed and replaced the headphones for each measurement repeat and were instructed simply to put the headphones on as they normally would.

Results are shown in Figure 2. The maximum frequency shown is 2 kHz, as data above that was not of interest for studying leakage.

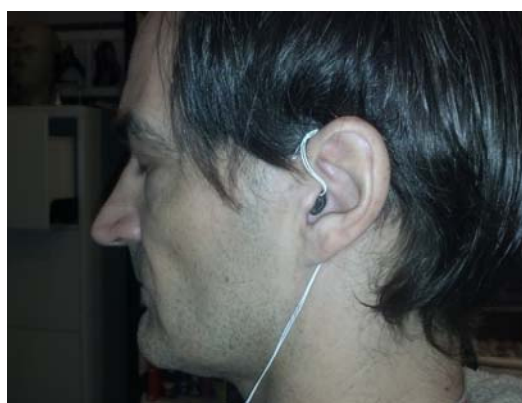


Figure 1 Custom in-ear microphones used for making blocked meatus measurements on test subjects.

## 2.2. Blocked meatus measurements on test subjects

Measurements were made on eight subjects using custom-made in-ear microphones, using Panasonic WM-64 electret capsules. Wires attached to the microphone capsules were very thin and flexible, so as not to cause any leakage when headphones were placed over them. Each microphone was individually measured and verified to be working properly and calibrated for subsequent measurements. Microphone calibration corrections were actually quite small above 50 Hz, and all analysis was restricted to >50 Hz to

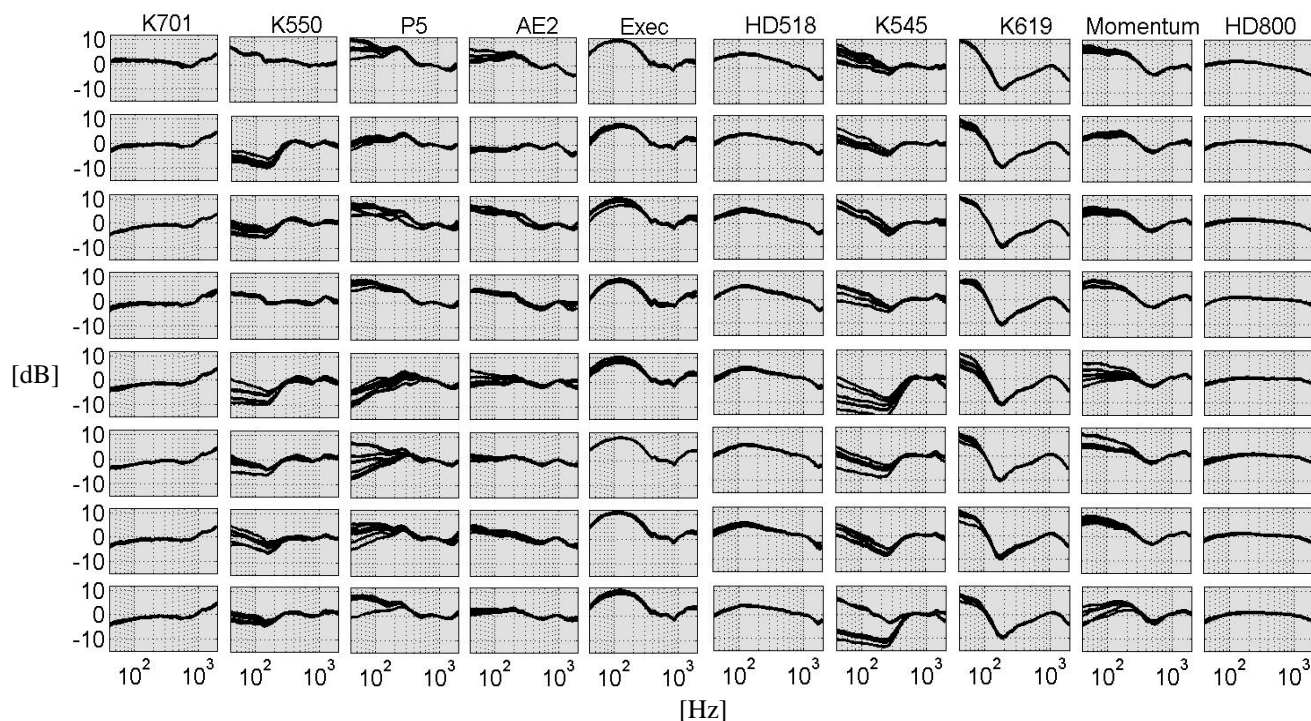


Figure 2 Measured blocked meatus responses of 10 headphones on 8 subjects, averaged left and right ear measurements. Each row is a different subject.

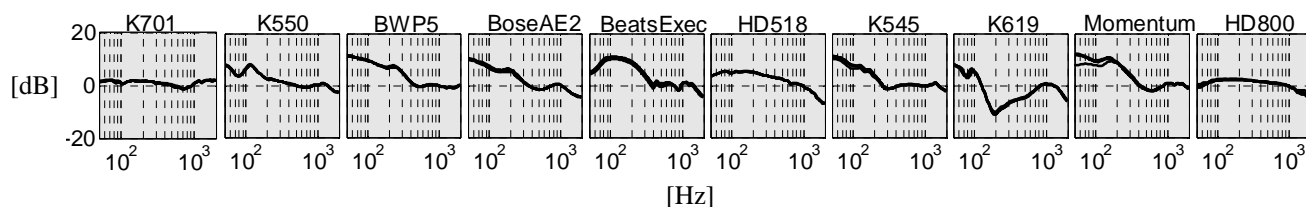


Figure 3 Measured responses of headphones on plates, averaged left and right ear measurements.

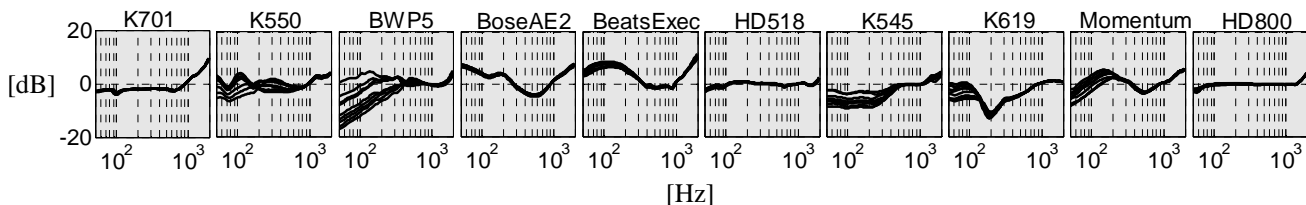


Figure 4 Measured responses of headphones using G.R.A.S KB0070/71 pinnae (IEC 60318-7) on 45CA test fixture, averaged left and right ear measurements.

As a measure of reliability of the blocked meatus measurements, a comparison of “day 1” versus “day 2” measurements was made indicating variation similar to reseating variation within a measurement session.

### 2.3. Plate Measurements

In order to get a baseline on the no-leakage condition, all headphones were measured on a test fixture consisting of a set of plates with flush mounted electret microphones on each side, which were centered under the headphone cup during measurements. The left and right ear plates were separated by 15.5 cm to match the breadth of a typical human head. The exact same type of microphone capsules and microphone preamp and calibration techniques were used as for the blocked meatus measurements. Each headphone was measured 6 times on the plates. Results are shown in Figure 3. It should be noted that the plate setup is not intended to measure real world leakage effects, since it gives a more or less perfect seal in all cases. It was included for comparison only.

### 2.4. G.R.A.S 45CA Test Fixture Measurements

The G.R.A.S 45CA test fixture includes integral IEC 60318-4 (formerly 60711) couplers and pinnae mounted on flat plates, angled and spaced to match the general contour of a typical human head. All headphones were measured on the G.R.A.S 45CA test fixture using three different sets of pinnae. In general, headphones were centered over the pinnae and placed for maximal seal. Completely removing the headphones between each measurement and making slight adjustments to the headband size helped ensure some variation in placement, such as would normally occur in real world use. Each headphone was measured nine times for each pinna type tested.

In contrast to the blocked meatus measurements, the reference point for the coupler measurements is not at the blocked ear canal, but at the ear Drum Reference Point (DRP). Comparison to blocked meatus reference point was simplified at low frequencies, where the response at the two reference points is essentially the same.



(a)



(b)

Figure 5 G.R.A.S 45CA test fixture (a); top view of IEC standard pinna on G.R.A.S 45CA test fixture (b). Note gap behind ear for BTE hearing aid.

The first pinna tested on the G.R.A.S fixture was the standard pinna set that comes with the 45CA fixture (KB0070/KB0071 Shore 00-55 large version). These pinnae generally conform to IEC 60318-7 [7]. Results are shown in Figure 4. Note that this pinna has a large gap behind the ear, which is intended to allow testing with Behind The Ear (BTE) hearing aids. This dimension is referred to as “protrusion” and is specified to be 19 mm. See Figure 5. This Shore 00-55 pinna is not as soft as a human ear. The protrusion and rigidity of this version of the IEC standard pinna can cause some headphones to sit awkwardly and leak excessively when placed on them. Refer to Figures 6 and 7.

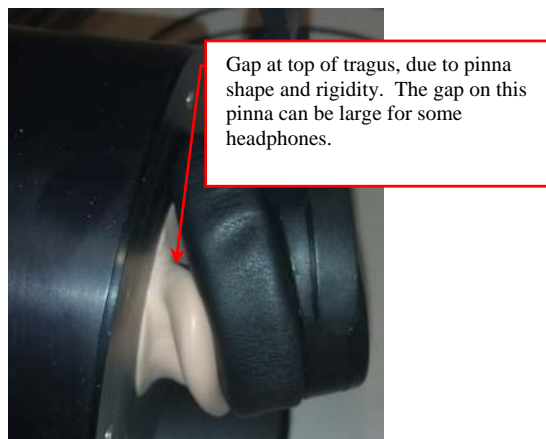


Figure 6 Top view of KB0070 IEC 60318-7 standard pinna on G.R.A.S 45CA test fixture with supra-aural headphones applied.

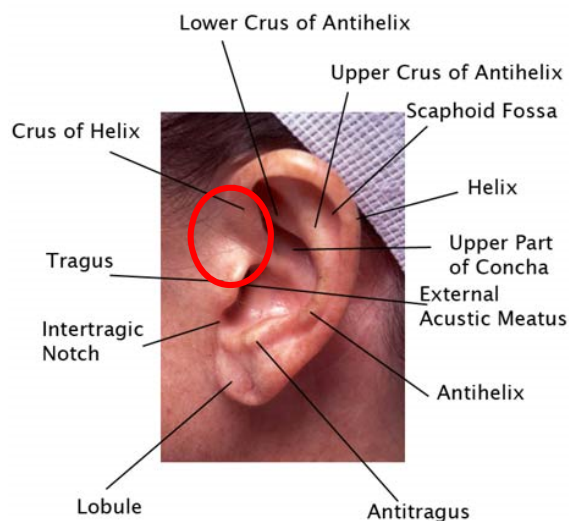


Figure 7 Side view of pinna anatomy showing the depression between the tragus and the crus of helix which can exaggerate leakage for supra-aural headphones measured on pinnae that are too rigid and/or protrude excessively.

Note that G.R.A.S. does make a softer (Shore 00-35) pinna with less protrusion, but it is not currently available on the 45CA test fixture. For these reasons, 3D CAD models of the IEC standard pinnae were made and then modified. The primary modification to the pinna shape was to rotate the entire pinna structure back significantly reducing the size of the gap behind it, and resulting in a protrusion of approximately 12 mm. An injection mold

was made from this modified model, and new pinnae cast using a Shore 00-35 silicon formulation (see Figure 8). This new set of pinna is referred to in this paper as “IEC Mod1”. In terms of protrusion and Shore hardness, IEC Mod1 pinnae are roughly analogous to some commercially available standard pinna models. After observing how a number of different headphones fit on the new pinnae, an additional modified version was constructed. The main difference to IEC Mod1 was that the new version was softer yet, below Shore 00-35. Some small additional structural changes were made based on observations of many headphones placed on the pinna. The second modified version is referred to as “IEC Mod2”.

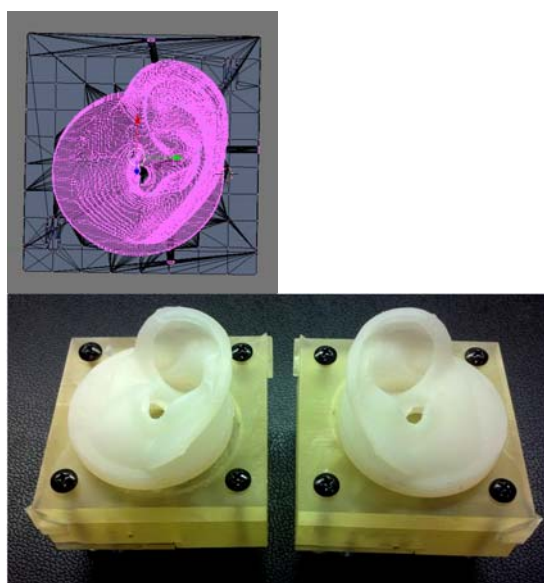


Figure 8 Modified CAD model of IEC 60318-7 standard pinna, and injection molded “IEC Mod2” pinna fabricated using the modified model.

Figures 9 and 10 show the measured responses of the IEC Mod1 and IEC Mod2 pinnae on the 45CA test fixture, using the same measuring methods as before. Figure 11 shows results for the three pinna types on the 45CA test fixture as well as the plate measurements. These curves have been normalized by subtracting out the blocked meatus responses, and thus show deviations from the reference blocked meatus responses. Overall gain differences, which are not of interest here, have also been removed. Figure 12 shows the data for all headphones on one plot. Figure 13 shows the averaged data over all headphones. All averaging is done arithmetically in dB.



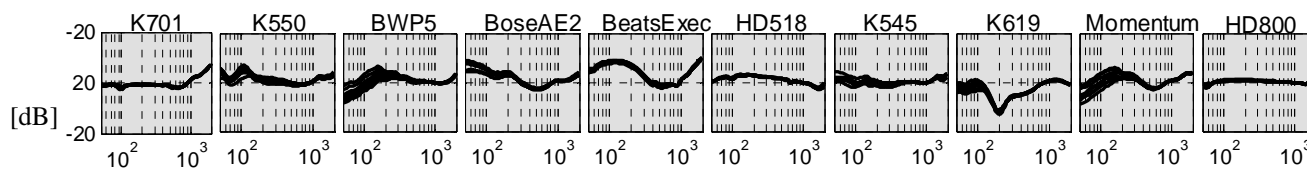


Figure 9 Measured responses of headphones using IEC 60318-7 pinnae (“IEC Mod1”) on 45CA test fixture, averaged left and right ear measurements.

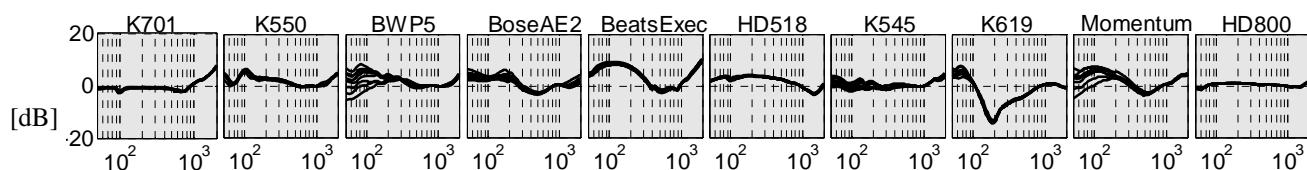


Figure 10 Measured responses of headphones using modified IEC 60318-7 pinnae (“IEC Mod2”) on G.R.A.S 45CA test fixture, averaged left and right ear measurements.

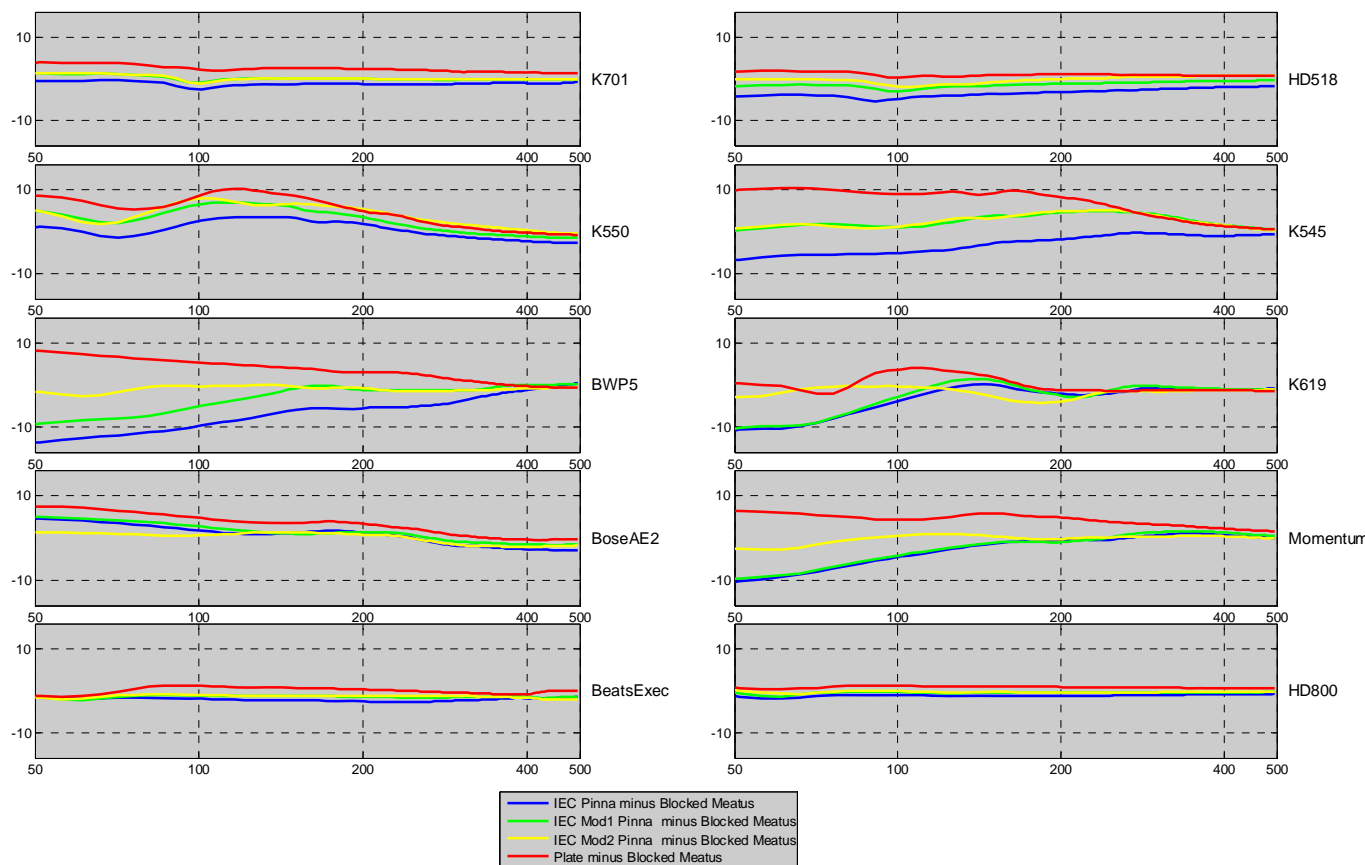


Figure 11 Comparison of the IEC pinnae, IEC Mod1 pinnae, IEC Mod2 pinnae, and plate measurements, averaged left and right ears. Curves were normalized by subtracting out the blocked meatus responses for each headphone.

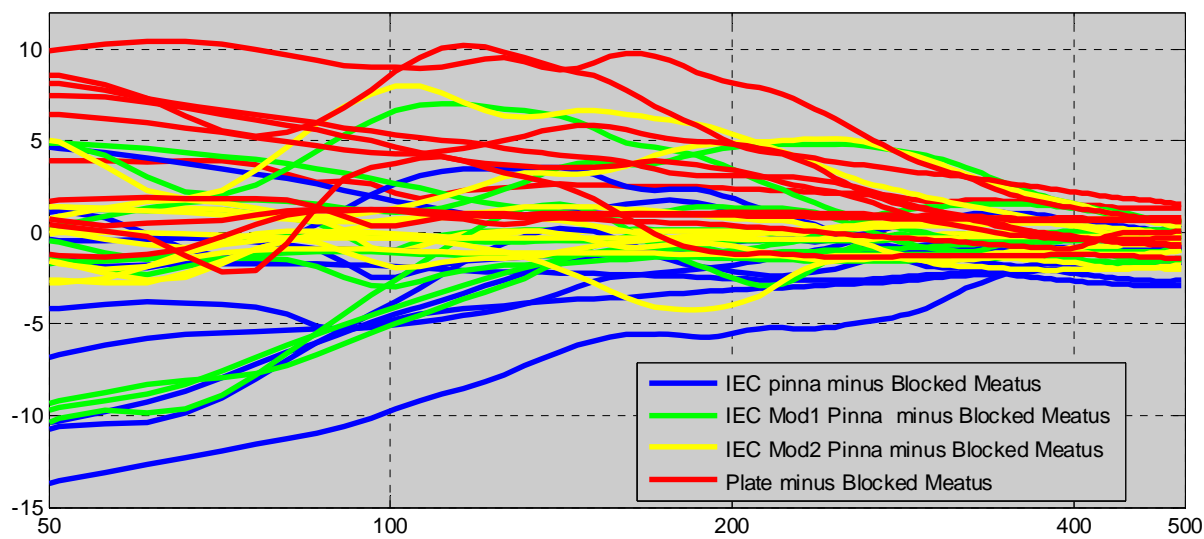


Figure 12 Comparison of the IEC pinnae, IEC Mod1 pinnae, IEC Mod2 pinnae, and plate measurements, averaged left and right ear. Curves were normalized by subtracting out the blocked meatus responses for each headphone, as well as overall gain differences between the headphone responses.

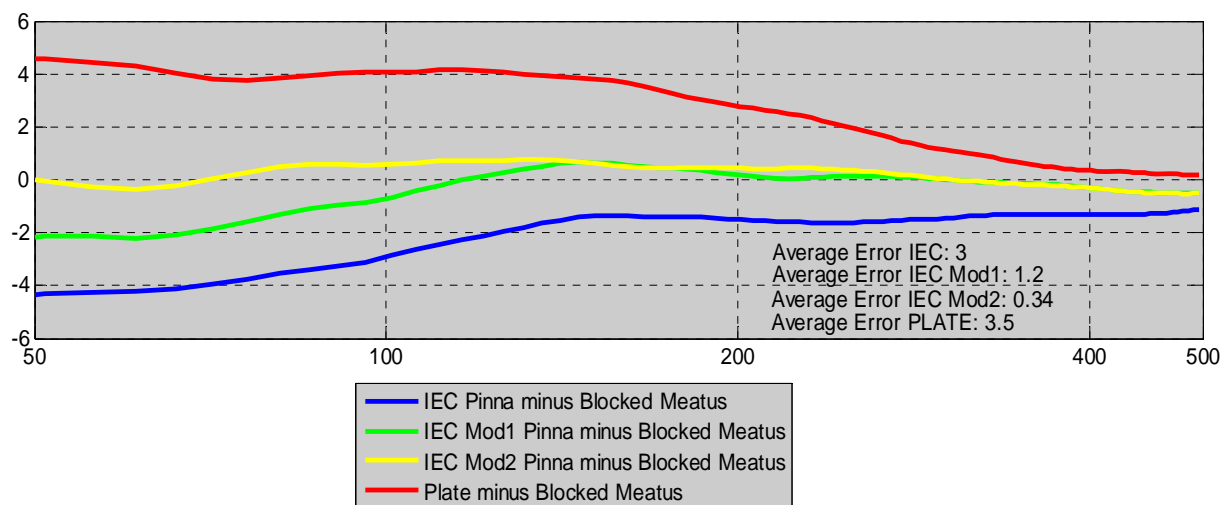


Figure 13 Same data as Figure 12, but averaged over all headphones. Average absolute value of error from 50-500 is shown.



### 3. DISCUSSION

Figures 11 and 12 show that for some headphones, different measurement techniques work better, i.e. are closer to the blocked meatus response. The plate method, which is not intended to measure leakage, generally over-represents the bass response of all headphones. A perfectly representative method would be zero at all points, i.e. no deviation from the reference blocked meatus response on a sampling of test subjects. In Figure 13, comparing all methods, it can be seen that the overall error was smallest for the IEC Mod2 pinnae. The average absolute value of the error (deviation from 0) was calculated for the frequency range of 50-500 Hz. Generally speaking, the plate measurement over-represents the bass response by about 3 dB, while the standard IEC pinnae under-represents the bass response by approximately 3 dB. Both the modified IEC pinnae had the lowest measurement error, with Mod2 having the lowest error at just 0.34 dB. These errors are larger at the lowest frequencies.

Looking at the data, one might expect the supra-aural headphones, which are sitting directly on the pinnae, to be most affected by pinna shape and pliability. Conversely circum-aural headphones, which do not rest on the pinnae might not be expected to be affected by differences in pinnae. The reality is more complicated. Many headphones do not fall 100% into one category or the other. For example, the Sennheiser Momentum headphones were on the small side for circum-aural headphones, tending to rest partially on the outer pinnae for many subjects. In addition, the area around the pinnae on the test fixture was flat (though angled slightly to match a human head). This is not true for test subjects, where the head is rounded. In particular, there tended to be leakage at the indentation between the jaw bone and mastoid process on human heads. This was not replicated in the simplified test fixture used. The result of these and other factors is complexity in the data, requiring a largish data set such as used in this investigation to observe the overall trends.

Additional complications arise from any discussion of hardness of pinnae. As noted in [8], different parts of the pinna have different hardnesses. Pinnae in this investigation were not directly tested for Shore hardness (estimates were based on Shore ratings for the silicone material used to make the pinnae). Comparisons to commercially available pinnae Shore ratings are thus

approximate. Tactile comparison of the IEC Mod2 pinna to other Shore 00-35 pinna (not used in this study) suggests that it was softer.

### 4. CONCLUSION

A large survey, including over 2000 individual measurements, was undertaken in order to compare leakage effects on test subjects and leakage effects of the same headphones measured on a test fixture. Modifications to the pinnae were investigated to see if the leakage effects measured on the test fixture could be made to better match the real word leakage effects measured on human test subjects. Modifications to the IEC standard pinnae included rotating the overall pinna structure back towards the head to minimize the large gap behind the ear, and using a softer more pliable silicone formulation. These modifications resulted in test fixture measurements that more closely matched blocked meatus measurements on test subjects. The improvement in accuracy for the IEC Mod2 pinna versus one version of the standard IEC pinnae was about 2.7 dB averaged from 50-500 Hz, and significantly more at the lowest frequencies.

### 5. FUTURE WORK

Additional testing of the modified pinnae on a head shaped test fixture is warranted, to determine if further improvements in accuracy can be achieved. Testing of insert type headphones vis a vis leakage is also of interest, as their leakage effects can be substantial.

### 6. ACKNOWLEDGEMENTS

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