9-2023

Absorbance Measurements From Normal-hearing Ears in the National Health and Nutrition Examination Survey, 2015–2016 and 2017–2020

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Recommended Citation

Sun, Jiayi; Horton, Nicholas J.; and Voss, Susan E., "Absorbance Measurements From Normal-hearing Ears in the National Health and Nutrition Examination Survey, 2015–2016 and 2017–2020" (2023). Engineering: Faculty Publications, Smith College, Northampton, MA.
https://scholarworks.smith.edu/egr_facpubs/144

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Abstract

Objective: To summarize absorbance and impedance angles from normal-hearing ears within the 2015-2016 and 2017-2020 U.S. National Health and Nutrition Examination Surveys (NHANES).

Design: Two publicly available NHANES datasets were analyzed. Ears meeting criteria for normal hearing and valid absorbance and impedance angle measurements were identified. Measurements were summarized via descriptive statistics within categories of age cohort, race/ethnicity cohort, sex (male, female), and ear (left, right).

Results: 7029 ears from 4150 subjects, ages 6-80 years, met inclusion criteria. Differences between subgroups within all categories (age, race/ethnicity, sex, ear) were fractions of the sample standard deviations. The largest differences occurred between age cohorts younger than 20 years.

Conclusions: The NHANES absorbance and impedance angle measurements are consistent with published literature. These results demonstrate that trained professionals, using the Titan instrument in a community setting inclusive of all demographics, produce comparable measurements to those in laboratory settings.

Keywords: wideband acoustic immittance, impedance angle, absorbance, NHANES

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1. Introduction

Objective noninvasive medical tests do not exist for many pathologies that occur within the auditory system. The development of a family of measurements known as wideband acoustic immittance (WAI), or equivalently referred to as wideband reflectance (WBR), includes absorbance and impedance measures, and has great potential for detecting a range of middle-ear problems from a noninvasive acoustic measurement made in the ear canal (e.g., Feeney, 2013). At the same time, ongoing and essential work continues in the areas of (1) describing normative WAI measurements and how such norms may or may not depend upon age, race, and sex and (2) challenges involved with ensuring that measurements are not corrupted by air leaks, calibration errors, or probes that are either clogged, oblique to the canal or against the canal's wall. Aspects of these important issues can be better understood through the analysis of data taken by the National Health and Nutrition Examination Survey (NHANES).

The NHANES program, which sits within the Center for Disease Control and Prevention's National Center for Health Statistics (National Health and Nutrition Examination Survey Data, 2022), collects a wide range of health-related survey and measurement data from a representative population across the United States. While data collection has historically included audiometric surveys and threshold levels, WAI measurements were first added in the 2015-2016 cycle and continued into the 2017-2020 cycle. The release of these WAI measurements along with additional audiometric measures provides a large community-based set of WAI data.

The NHANES WAI data associated with normal-hearing ears are summarized here and are available for download on both (1) the NHANES website which includes all WAI measurements made within the NHANES program (National Health and Nutrition Examination Survey Data, 2015-2016, 2017-2020) and (2) the literature-based WAI database website hosted by our group at Smith College (Voss and Horton, 2022).

2. Materials and Methods

2.1. NHANES database overview

Two independent cohorts of wideband acoustic immitance (WAI) data have been published to the National Health and Nutrition Examination Survey Data (NHANES) website. The 2015-2016 NHANES data includes WAI measurements on subjects ages 20-69 years, and the 2017-2020 NHANES data includes WAI measurements on subjects ages 6-19 and 70-80 years. The NHANES website includes multiple files with subject-specific demographics, audiometric data, and WAI data. The WAI quantities of absorbance and admittance angle at ambient ear-canal pressure were reported within the scope of the NHANES databases; the quantity of admittance magnitude was not reported, and we have confirmed with the CDC that the admittance magnitude was not saved during data collection. Here, we transform the reported admittance phase to impedance, which we refer to as impedance angle, to be consistent with the format of the literature-based WAI database (Voss, 2019; Voss and Horton, 2022).

Overview of NHANES measurement methodology

NHANES data were collected within mobile examination centers (MEC) by trained professionals who traverse the United States of America. Measurements were made on subjects who were invited to and agreed to participate, with the goal of being representative of the noninstitutionalized U.S. civilian population (e.g., meeting set racial and ethnicity goals). Hearing-related measurements were conducted within a dedicated sound-isolating room of the MEC (trailer #3); detailed audiometry procedures manuals are available online (National Health and Nutrition Examination Survey Data: Audiometry Procedures, 2015-2016, 2017-2020). Briefly, each subject completed a hearing-related questionnaire, otoscopic examination, air-conduction audiometry, and the three middle-ear immittance measurements of tympanometry, wideband reflectance (WBR) at ambient pressure, and acoustic reflex threshold screening. All WBR measurements were made at ambient ear-canal pressure with the Titan instrument from Interacoustics, which reports measurements at 107 linearly spaced frequencies from 226-8000 Hz. The quantities of absorbance and admittance angle were reported within the NHANES datasets at all 107 frequencies. We note that the procedure manual incorrectly claims "Because WBR [wideband reflectance] makes measures just at the background room air pressure, it does not require an airtight seal". In fact, absorbance and impedance measurements are extremely sensitive to acoustic leaks between the instrument's probe and the canal wall, as further discussed in the work presented below.

2.2. Definition for and inclusion of normal ears only

Ears that met the following four criteria were defined as normal and selected for inclusion in the normative data reported here: (1) Normal otoscopy upon examination, (2) pure-tone thresholds $\leq$ 20 dB at frequencies 500, 1000, 2000, and 4000 Hz, (3) tympanometric peak pressures in the range -50 to 50 daPa, and (4) tympanometric compliance in the range 0.3 to 1.5 mmho (Keefe et al., 2017; Downing et al., 2022). Within the 2015-2016 dataset (ages 20-69 years), audiometric measurements were reported from 4582 subjects (8554 ears); a total of 3609 of these ears met the normal-hearing inclusion criteria. Within the 2017-2020 dataset (ages 6-19 and 70-80 years), audiometric measurements were reported from 5147 subjects (9234 ears); 3420 ears met the normal-hearing inclusion criteria.

2.3. Data selection criteria (DSC)

WAI measurements can be corrupted by leaks in the acoustic seal between the measurement probe and canal walls (acoustic leak), calibration errors, clogged probes, and probes that are either oblique to the canal or against the canal's wall. Thus, we applied a data selection criteria (DSC) to each ear's measurements; when either the absorbance or impedance angle measurement did not meet the DSC, that ear's measurements were excluded from further analyses.

Groon et al. (2015) provided criteria for the identification of acoustic leaks using the bandwidth 200-500 Hz; specifically they determined that a leak was likely when the average absorbance exceeded 0.29 or the average impedance angle exceeded -0.12 cycles. However, the Groon et al. (2015) 200-500 Hz range included 51 measurements with a frequency resolution of 5.86 Hz, whereas the Titan system used for the NHANES data collection had a 226-500 Hz range that included 13 measurements with a frequency resolution of 31.32 Hz. The average absorbance and impedance angle are heavily influenced by the lower end of the available frequency range because these quantities generally increase systematically from 200-500 Hz.

To address this issue, we applied modified criteria due to the issue of the Titan lacking data for the lowest 8% of the Groon et al. (2015) criteria's frequency range where the measurement values are the smallest. Specifically, to select measurements with probable leaks we defined the DSC as the average from eight points at frequencies from 226 to 385 Hz (instead of 200-500 Hz) and used upper limits of 0.3 for absorbance and -0.13 for the impedance angle. We note that there is no way to directly map the Groon et al. (2015) criteria to the Titan's frequency range. The DSC applied here were less stringent than those from Groon et al. (2015); for example, when the Groon et al. (2015) absorbance and impedance angle criteria were applied across the Titan's available 226-500 Hz range, an additional 848 measurements were eliminated as compared to what is presented in the lower panel of Fig. 1 which used the DSC outlined here.

The effects and causes of calibration errors on WAI measurements are less well studied than the effects of acoustic leaks. In general, calibration errors likely result from changes in the equipment between the time of measurements and calibration, which could be caused by a partially clogged probe or a change in the orientation of or compression on the probe within the canal. One clear sign of a calibration error is when the WAI measurements are "out of range", which we defined as measurements with values that are outside the range that is physically possible. We defined the DSC to identify measurements that are out of range as: (1) The absorbance value was less than zero at five or more frequencies of the measurement, or (2) The impedance angle was either less than -0.25 cycles or greater than 0.25 cycles at five or more frequencies of the measurement. We chose the out of range DSC to cover the frequency range 200-6000 Hz and not to the upper limit of the NHANES data (8000 Hz) to be consistent with many published WAI measurements with upper measurement limits of 6000 Hz.

The DSC were applied to measurements from all ears identified as normal hearing. First, the out of range DSC were applied to the measurements from all ears, and appropriate measurements were labeled as "Out of Range". Next, the DSC for an air leak were applied to the remaining ears, and appropriate measurements were labeled as "Probable Leak". All remaining measurements were labeled as "Meet Criteria".

We note that WAI measurements can also be corrupted by probes that are wedged against the ear canal wall, which may or may not lead to out of range measurements. Voss et al. (2016) suggested this condition might be identified by the WAI measurement of impedance magnitude exceeding the normal range, due to a small air volume terminating the probe. The NHANES datasets cannot be evaluated for this possibility because the impedance magnitudes were not saved as part of the data collection process.

2.4. Demographics for ears that met the data selection criteria

One goal of the NHANES program is for the subject demographics to be representative of the entire population of the United States. While we started with all subjects within the NHANES databases that included WAI measurements, the demographics of the collection of normal-hearing ears for which the WAI measurements met the DSC are not identical to the original NHANES demographics. Table 1 categorizes the numbers of subjects and ears that were included in the WAI analyses for the normal-hearing ears.

2.5. Statistical Analyses

Analysis of variance calculations were performed with the Matlab (ver 2021b) function “anova1”.

3. Results

Figure 1 summarizes all absorbance (left column) and impedance angle (right column) measurements made on the 7029 normal-hearing ears within the NHANES programs from 2015-2020. The upper row plots measurements from the 5591 (80%) of these ears that met the DSC; the middle row plots measurements from the 850 ears (12%) that produced out of range measurements; and the lower row plots measurements from the 588 ears (8%) identified as including probable leaks. We note that it is likely that some of the measurements in the out of range category were also affected by leaks.

Figure 2 summarizes the data by comparing measurements within the categories of age cohort (upper row), race cohort (upper-middle row), sex (lower-middle row), and left/right ears (lower row). The groups within each of these categories were chosen to summarize the data while keeping the number of groupings small enough to ensure visibility.

Differences between the groups in each category are relatively small fractions of the standard deviations of the entire sample absorbance and impedance angle; the standard deviations are largely homogeneous between all groups (not shown) and to simplify the plots we summarize them using the overall standard deviation. The largest group differences occur within the age cohort category, with the younger three cohorts (spanning 6-19 years) showing systematic differences from the two adult cohorts (spanning 20-80 years). Specifically, the younger cohorts show slightly lower absorbance means below about 1000 Hz. In the range of about 1500-5000 Hz, the absorbance means for the three younger cohorts show a systematic increase in absorbance with decreasing age cohort; at these higher frequencies the larger differences between the means of the youngest and oldest age cohorts approach one half of a standard deviation of the sample mean. Similarly, there are also age-cohort effects in the impedance angle, with younger age cohorts exhibiting larger angles than the adults in the 1000-2000 Hz region, and the younger age cohorts exhibiting smaller impedance angles in the 4000-6000 Hz range. The largest differences in impedance angle are on the order of about two thirds of a standard deviation of the sample mean.

The remaining three categories – race cohort, sex, and left/right ears - show minimal differences in absorbance and impedance angle within their respective groups. In all cases, differences between the groups are generally well below one half of the standard deviations of the entire population's absorbance and impedance angle.

To help quantify the observed group differences in absorbance and angle, we carried out an analysis of variance for age cohort, race cohort, sex, and left/right ears. To reduce the number of tests, we adopted a reviewer suggestion and picked the single frequency of 2000 Hz across all groups comparisons. All eight overall F-tests were highly significant (all p-values < 0.0001), which is not unexpected given the large number of measurements (n=5591).

4. Discussion

Figure 3 compares the NHANES normal-hearing measurements to published measurements from Downing et al. (2022); Groon et al. (2015), and Rosowski et al. (2012); these three studies were chosen because their results are representative of the larger literature. An important conclusion from Figure 3 is that the NHANES measurements are consistent with the wider WAI literature. This result demonstrates that trained professionals using the Titan instrument, in a community setting inclusive of all demographics, produce similar results as measurements taken by researchers in laboratory settings. At the same time, we note that 20% of the measurements did not meet the DSC. As researchers develop a better understanding of how WAI data can be corrupted during the measurement process, improvements in the automation of measurement systems like the Titan can be applied in real time to measurements. While it was possible here to remove measurements that were clearly corrupted (out of range and probable leaks), more work is needed to determine appropriate data selection criteria for measurements that are either from very young ears or ears that are not normal – such populations would have data selection criteria that differ from the normal-hearing, 6-years-and-older population considered here. Additionally, more research is needed in all populations to differentiate valid from corrupt measurements in cases where the probe is either clogged, oblique to the canal or against the canal's wall.

We also offer a few thoughts on some details within the summary means plotted in Figure 3. The NHANES data were collected with version 3 of the Titan Suite measurement system (Interacoustics, 2022), which appears to result in a characteristic pattern with small and systematic oscillations in frequency in all of the means; it is likely that this pattern results from slight imperfections in the calibration cavities associated with version 3 of the Titan. The Downing et al. (2022) measurements were collected with version 4 of the Titan system which has an updated calibration cavity design and no measurement oscillations. Nonetheless, the two systems produced similar results across similar age groups. The Groon et al. (2015) data were collected with a lab-specific system that used a probe similar to that in the commercial Titan, and the Rosowski et al. (2012) data were collected with the commercial HearID system from Mimosa Acoustics (Mimosa Acoustics, 2022). It is notable that the low-frequency absorbance means from these latter two studies show a larger gap than other comparisons in the plot. One explanation is the location of the probe tip for the two systems; the Titan-based probe tip used by Groon et al. (2015) likely sits more laterally in the ear canal than the HearID-based probe tip used by Rosowski et al. (2012), effectively leading to a deeper insertion associated with the Rosowski et al. (2012) data. Abur et al. (2014) showed a similar systematic difference of about 0.1 in absorbance below 1000 Hz with differences in insertion depth of 6 mm; thus, it seems likely that these differences in low-frequency absorbance result from different probe placements. Data selection criteria may also need to consider probe placement when using low-frequency absorbance values as a criterion.

This work has used descriptive statistics to summarize the largest-to-date WAI dataset taken on normal-hearing ears within a community setting across a broad demographic. Differences in absorbance and impedance angle were nominal within the categories of age cohort, race cohort, sex, and left/right ears. While there were some systematic trends, most of the group differences were far smaller than the corresponding standard deviations; the largest variations occurred when age was the parameterized category and between the younger age groups. To examine the small systematic differences within each of the four categories, one would need to account for the multiple comparisons inherent with 107 measurement frequencies and the various age and race groups chosen for analyses, along with sex and ear side. While an analysis of variance did demonstrate significant differences among groups at 2000 Hz, and similar analyses would result in significant differences among groups at additional frequencies, caution must be taken in reading too much into these small differences due to the complications of multiple comparisons. Additionally, statistical significance of small differences, which result from a large number of measurements, is less important than whether or not the differences among the groups are clinically significant. In fact, the findings that all groups have very similar standard deviations that are far larger than inter-group differences suggests that most of the reported differences among groups are likely clinically insignificant.

Acknowledgments

This work was funded by grant R15 DC014129 from the National Institutes of Health NIDCD. We thank Kren Nørgaard for helpful conversations about the calibration cavities associated with version 3 of the Titan instrument.

References

Abur, D., Horton, N., Voss, S., 2014. Intra-subject variability in power reflectance. Journal of the American Academy of Audiology 25, 441–448.

Downing, C., Kei, J., Driscoll, C., Choi, R., Scott, D., 2022. Wideband tympanometry findings in school-aged children: Effects of age, gender, ear laterality, and ethnicity. Ear Hearing 43, 1245–1255.

Feeney, M.P., 2013. Eriksholm workshop: Wideband absorbance measures of the middle ear. Ear Hearing 34. Supplement 1.

Groon, K., Rasetshwane, D., Kopun, J., Gorga, M., Neely, S., 2015. Air-leak effects on ear-canal acoustic absorbance. Ear Hearing 36, 155–163.

Interacoustics, 2022. URL: `https://www.interacoustics.com/us/`. (accessed: 2022-08-21).

Keefe, D., Archer, K., Schmid, K., Fitzpatrick, D., Feeney, M., Hunter, L., 2017. Identifying otosclerosis with aural acoustical tests of absorbance, group delay, acoustic reflex threshold, and otoacoustic emissions. J. Am. Acad. Audiol. .

Mimosa Acoustics, 2022. URL: `https://www.mimosaacoustics.com/`. (accessed: 2022-08-21).

National Health and Nutrition Examination Survey Data, 2015-2016. Centers for Disease Control and Prevention (CDC). National Center for Health Statistics (NCHS). Hyattsville, MD: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention. URL: `https://wwwn.cdc.gov/nchs/nhanes/default.aspx`. (accessed: 2022-08-01).

National Health and Nutrition Examination Survey Data, 2017-2020. Centers for Disease Control and Prevention (CDC). National Center for Health Statistics (NCHS). Hyattsville, MD: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention. URL: `https://wwwn.cdc.gov/nchs/nhanes/default.aspx`. (accessed: 2022-08-01).

National Health and Nutrition Examination Survey Data, 2022. Centers for Disease Control and Prevention (CDC). National Center for Health Statistics (NCHS). Hyattsville, MD:

U.S. Department of Health and Human Services, Centers for Disease Control and Prevention. URL: `https://www.cdc.gov/nchs/nhanes/index.htm`. (accessed: 2022-08-01).

National Health and Nutrition Examination Survey Data: Audiometry Procedures, 2015-2016. Hyattsville, MD: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention. URL: `https://wwwn.cdc.gov/nchs/nhanes/continuousnhanes/manuals.aspx?BeginYear=2015`. (accessed: 2022-11-22).

National Health and Nutrition Examination Survey Data: Audiometry Procedures, 2017-2020. Hyattsville, MD: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention. URL: `https://wwwn.cdc.gov/nchs/nhanes/continuousnhanes/manuals.aspx?Cycle=2017-2020, note = "(accessed: 2022-11-22)",`.

Rosowski, J.J., Nakajima, H.H., Hamade, M., Mahfoud, L., Merchant, G.R., Halpin, C.F., Merchant, S.N., 2012. Ear-canal reflectance, umbo velocity, and tympanometry in normal hearing adults. Ear Hearing 33, 19–34.

Voss, S., Horton, N., 2022. Wideband Acoustic Immittance Database URL: `https://scholarworks.smith.edu/dds_data/6`.

Voss, S.E., 2019. Resource review: An online wideband acoustic immittance (WAI) database and corresponding website. Ear Hearing 40, 1481.

Voss, S.E., Herrmann, B.S., Horton, N.J., Amadei, E.A., Kujawa, S.G., 2016. Reflectance measures from infant ears with normal hearing and transient conductive hearing loss. Ear Hearing 37, 560–71.

Table 1: Demographics for both NHANES datasets. The NHANES demographic field of "RIDRETH3 - Race/Hispanic origin w/ NH Asian" was used to create four race/ethnicity groupings reported here. Three groups come directly from the NHANES coding and are: (1) Non-Hispanic White, (2) Non-Hispanic Black, and (3) Non-Hispanic Asian. Our fourth group (4) "Other" combines the remaining NHANES groups of Mexican American, Other Hispanic, and Other Race - Including Multi-Racial. The column labeled # Ears reports the total number of ears that met the data selection criteria (DSC); in some subjects only a single right or left ear met the criteria and in other subjects both ears met the criteria.

NHANES 2015-2016 (Ages 20-69 years)					
Group	# Subjects	Right only	Left only	Both Ears	# Ears
All Normal-Hearing Subjects	2174	359	380	1435	3609
Meet Data Selection Criteria (DSC)	1851	428	400	1023	2874
– Non-Hispanic White (meet DSC)	541	148	125	268	809
– Non-Hispanic Black (meet DSC)	412	88	84	240	652
– Non-Hispanic Asian (meet DSC)	257	44	54	159	416
– Other (meet DSC)	641	148	137	356	997
– Male (meet DSC)	673	185	166	322	995
– Female (meet DSC)	1178	243	234	701	1879

NHANES 2017-2020 (Ages 6-19 and 70-80 years)					
Group	# Subjects	Right only	Left only	Both Ears	# Ears
All Normal-Hearing Subjects	1976	259	273	1444	3420
Meet Data Selection Criteria (DSC)	1731	395	350	986	2717
– Non-Hispanic White (meet DSC)	557	132	117	308	865
– Non-Hispanic Black (meet DSC)	433	102	103	228	661
– Non-Hispanic Asian (meet DSC)	137	30	24	83	220
– Other (meet DSC)	604	131	106	367	971
– Male (meet DSC)	836	215	176	445	1281
– Female (meet DSC)	895	180	174	541	1436

Figure Captions

Figure 1: WAI measurements of absorbance (left column) and impedance angle (right column). In each plot, thin lines are individual measurements that correspond to “Meet Data Selection Criteria” (upper, n=5591), “Out of Range” (middle, n=850), and “Probable Leak” (lower, n=588). The measurements that meet the data selection criteria (upper row) are summarized by their median (thicker black line), their 25-75% range of data (thinner black line), and their 5-95% range of data (yellow dotted lines); these summary statistics for the measurements meeting the data selection criteria are included on all plots to aid in visual comparisons across the groups.

Figure 2: Comparisons of WAI measurements within the categories of age cohort (upper row), race cohort (upper-middle row), male/female (lower-middle row), and left/right ears (lower row), each broken into appropriate groups. The four columns show the mean absorbance for each group (left column), the differences in absorbance between the groups (left-center column), the impedance angle for each group (right-center column), and the differences in angle between the groups (right column). In each plot, solid lines are the means or the mean differences that correspond to the group within the row’s legend; lightly dashed lines indicate 5-95% range of the plotted quantities; and the dashed black lines on the difference plots show the standard deviation for the absorbance and impedance angle calculated from all measurements (Fig. 1, upper row, n=5591). Plots of differences (left-center and right columns) are relative to the quantity at the bottom of the respective legend and are defined in the labels on the y-axes.

Figure 3: Comparison of WAI measurements of mean absorbance (left column) and mean impedance angle (right column) between the NHANES data from this work and published studies. The NHANES data are summarized by plotting the NHANES mean data from the two age groups that are most different from the overall NHANES mean. Impedance angle data are not available for Downing et al. (2022). The comparison data were plotted by accessing them through the WAI database hosted at Smith College (Voss and Horton, 2022).

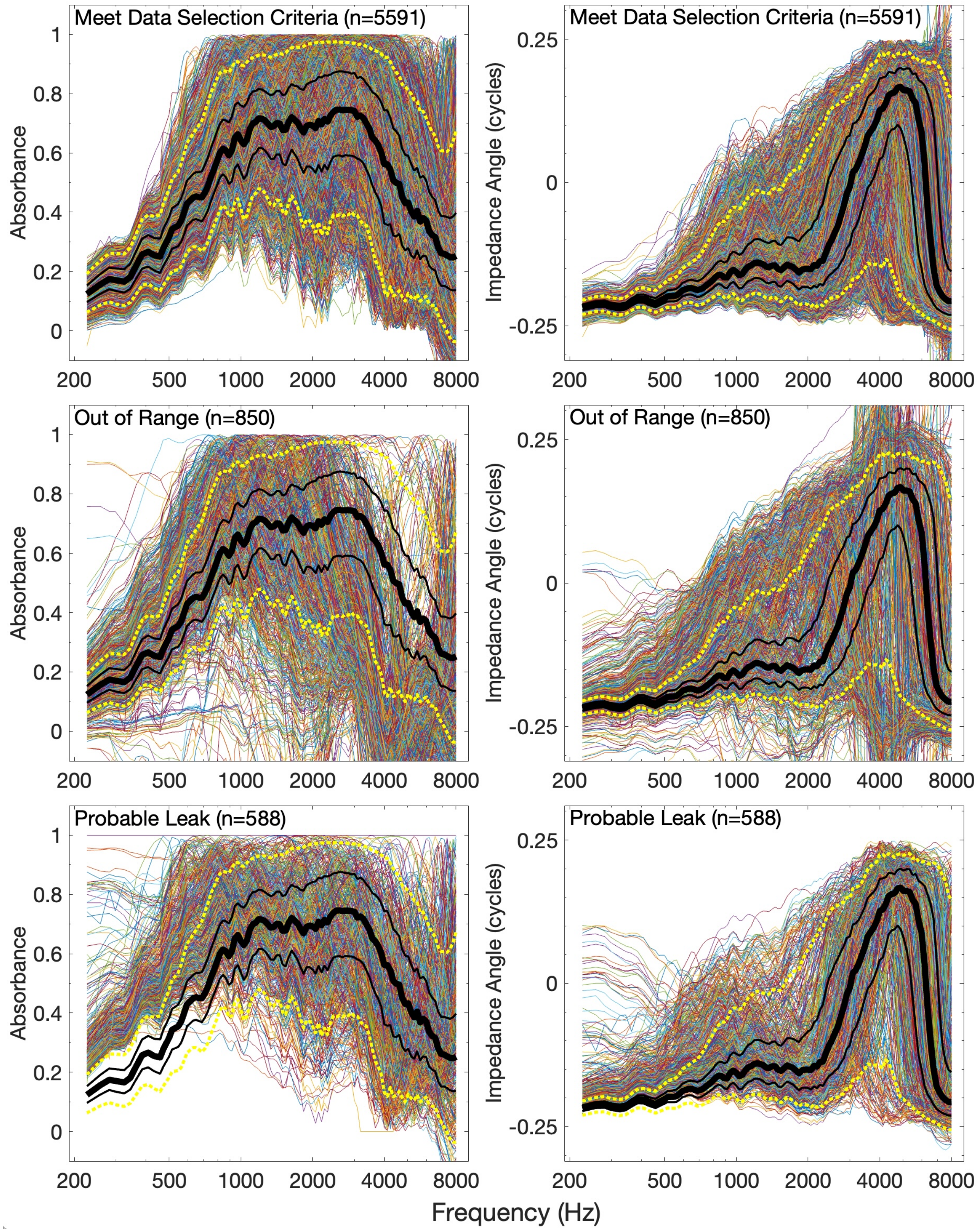
Meet Data Selection Criteria (n=5591)
Absorbance
Impedance Angle (cycles)
Out of Range (n=850)
Probable Leak (n=588)
0
0.2
0.4
0.6
0.8
1
-0.25
0
0.25
200
500
1000
2000
4000
8000
Frequency (Hz)

Figure 1:

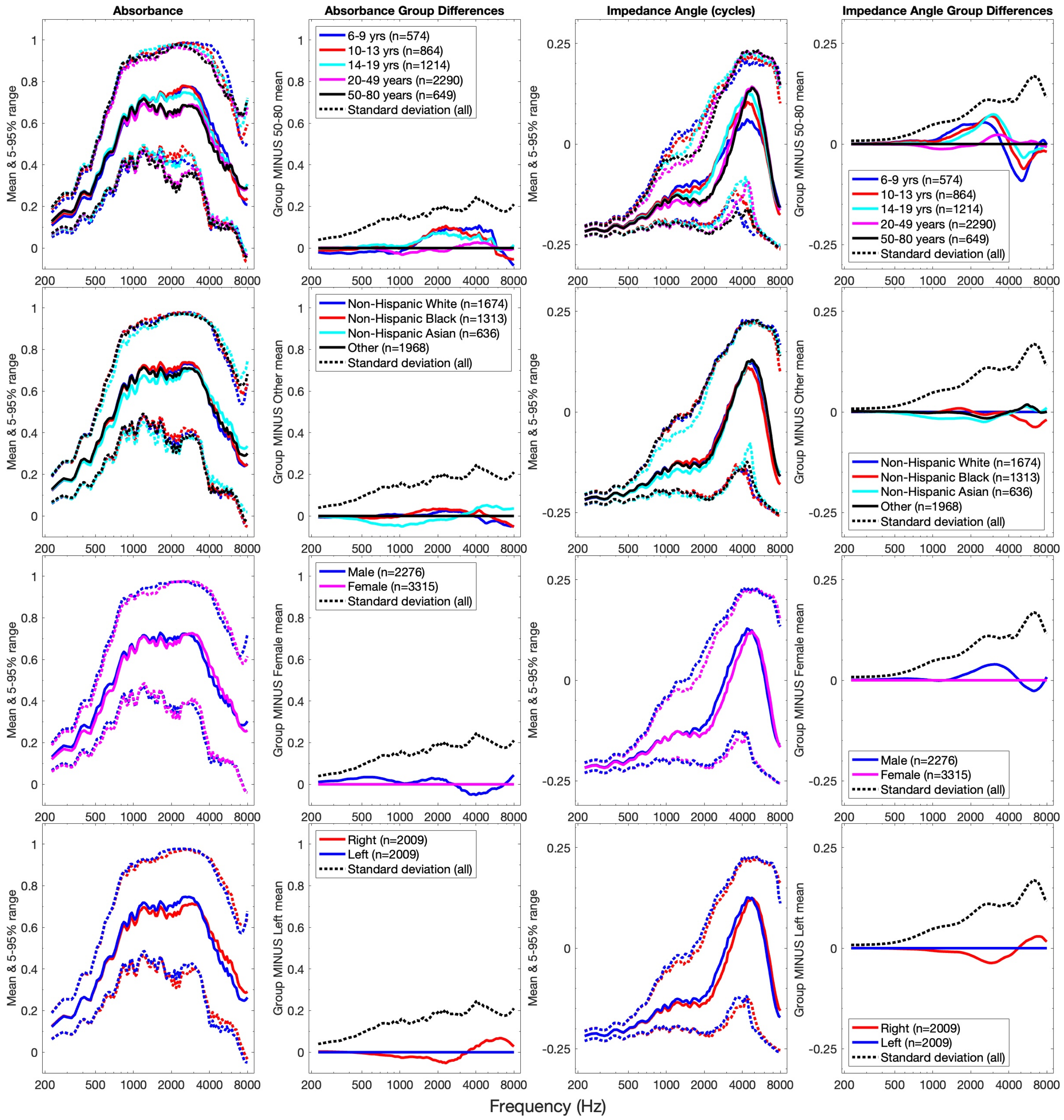
Absorbance
Absorbance Group Differences
Impedance Angle (cycles)
Impedance Angle Group Differences
Mean & 5-95% range
Group MINUS 50-80 mean
Group MINUS Other mean
Group MINUS Female mean
Group MINUS Left mean
6-9 yrs (n=574)
10-13 yrs (n=864)
14-19 yrs (n=1214)
20-49 years (n=2290)
50-80 years (n=649)
Standard deviation (all)
Non-Hispanic White (n=1674)
Non-Hispanic Black (n=1313)
Non-Hispanic Asian (n=636)
Other (n=1968)
Male (n=2276)
Female (n=3315)
Right (n=2009)
Left (n=2009)
0
0.2
0.4
0.6
0.8
1
-0.25
0
0.25
200
500
1000
2000
4000
8000
Frequency (Hz)

Figure 2:

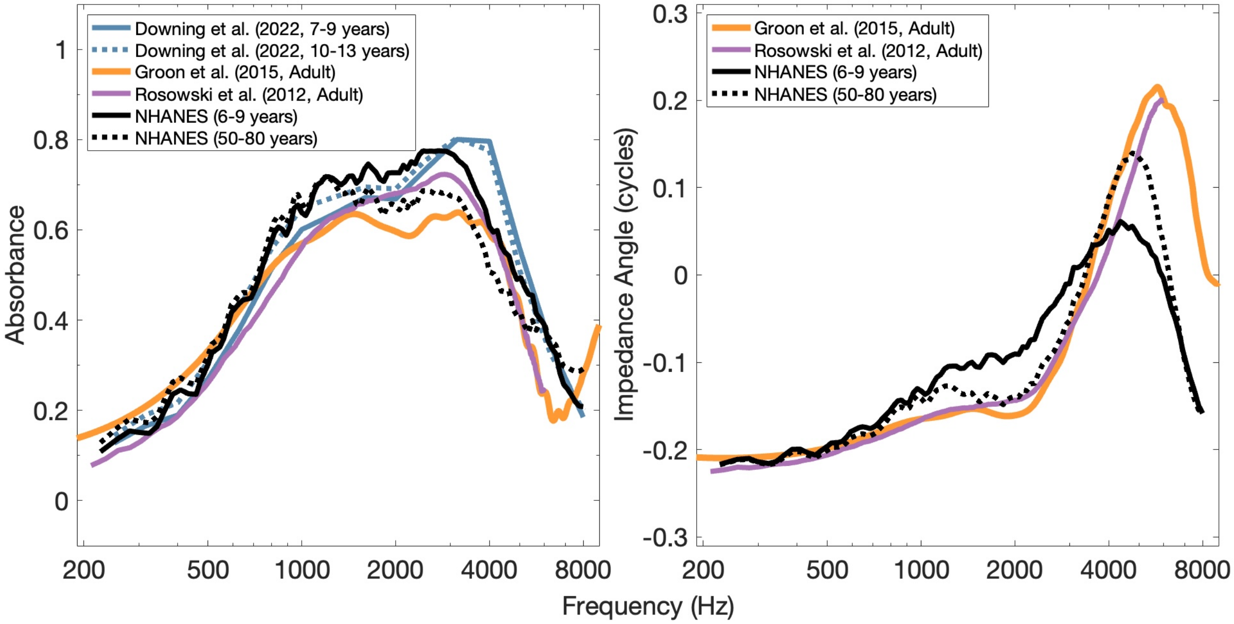
Downing et al. (2022, 7-9 years)
Downing et al. (2022, 10-13 years)
Groon et al. (2015, Adult)
Rosowski et al. (2012, Adult)
NHANES (6-9 years)
NHANES (50-80 years)
Absorbance
0
0.2
0.4
0.6
0.8
1
200
500
1000
2000
4000
8000
Groon et al. (2015, Adult)
Rosowski et al. (2012, Adult)
NHANES (6-9 years)
NHANES (50-80 years)
Impedance Angle (cycles)
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
200
500
1000
2000
4000
8000
Frequency (Hz)

Figure 3: