Sound Attenuation in Audiometric Testing: A Review of Single-Walled Booths and Boothless Technologies for Occupational Hearing Screening

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Abstract

This white paper investigates the sound attenuation performance of typical single-walled, small audiometric test booths and an emerging boothless audiometry system (Kuduwave), specifically focusing on the 125-8000 Hz frequency range critical for comprehensive occupational hearing screening. Accurate hearing assessment in workplace environments is paramount, and ambient noise, including at lower frequencies which can cause upward spread of masking, can significantly compromise test validity. This paper reviews manufacturer-specified noise reduction (NR) data for a range of commercially available single-walled booths, including Amtronix, presented in comprehensive tables, and the Kuduwave boothless system across key audiometric octave band frequencies from 125 Hz to 8000 Hz. The analysis reveals average, minimum, and maximum NR values for these booths across this broader frequency spectrum. The Kuduwave system's attenuation figures are compared against the average performance of single-walled booths. These findings are discussed in the context of established audiometric testing standards, ANSI/ASA S3.1-1999 (R2018), ISO 8253-1:2010, and SANS 10182, which define maximum permissible ambient noise levels (MPANLs/MPASPLs). The paper highlights considerable variability in performance among single-walled booths, particularly at lower frequencies (125 Hz and 250 Hz). This inherent variability necessitates a shift from reliance on broad categorizations to detailed, model-specific data evaluation by end-users, as the general label "single-walled booth" encompasses a heterogeneous range of acoustic capabilities across the full audiometric spectrum. The paper also notes the distinct approach of boothless systems, emphasizing that selection for occupational screening must be guided by site-specific ambient noise conditions across all relevant frequencies and careful scrutiny of manufacturer data.

1. Introduction

The validity and reliability of audiometric test results, particularly in occupational health settings, are fundamentally dependent on a controlled acoustic environment. The presence of undesirable ambient noise within the testing space can mask the pure-tone signals used in air conduction audiometry, leading to elevated (i.e., poorer) hearing thresholds. Such inaccuracies can result in misclassification of hearing status, inappropriate management of hearing conservation programs, or erroneous assessments of work-related hearing loss, all of which carry significant financial and legal implications.[1] Consequently, the use of sound-attenuating enclosures, commonly known as audiometric booths, is standard practice in industrial and clinical settings to isolate the test subject from external noise sources. While historically focused on the 500-8000 Hz range critical for monitoring occupational noise-induced hearing loss, effective control of ambient noise across the broader 125 Hz to 8000 Hz spectrum is essential for comprehensive and accurate assessment.[1] Lower frequencies, such as 125 Hz and 250 Hz, though not always the primary frequencies for tracking noise-induced damage, can significantly interfere with testing at higher frequencies through the phenomenon of upward spread of masking.[1]

This white paper aims to systematically review and analyze the sound attenuation performance, specifically Noise Reduction (NR) or Transmission Loss (TL), of commercially available, typical single-walled, small audiometric test booths relevant to occupational hearing screening. The analysis focuses on determining the average, minimum, and maximum attenuation values across the standard audiometric frequencies from 125 Hz to 8000 Hz, based on manufacturer-provided data and relevant supporting documents. This performance is then contextualized against an alternative boothless audiometry approach, exemplified by the Kuduwave system.

The importance of this analysis is underscored by the need for occupational health professionals, audiologists, and facility managers to select audiometric solutions that can effectively reduce external ambient noise to levels compliant with established testing standards, such as the American National Standards Institute (ANSI) S3.1, the International Organization for Standardization (ISO) 8253-1, and the South African National Standard (SANS) 10182.[1] Achieving these internal noise levels across the full frequency range is paramount for accurate hearing assessment in the workplace. The very existence of detailed standards like ANSI S3.1, ISO 8253-1, and SANS 10182, which meticulously specify maximum permissible ambient noise levels inside the test room, implies a fundamental challenge: typical industrial or workplace environments are often too noisy to permit accurate audiometry without acoustic intervention.[1] These standards define the target internal acoustic environment, and sound booths are a primary engineering control used to achieve this target by sufficiently attenuating external noise. Furthermore, the emergence and investigation of "boothless" audiometry techniques, which employ specialized transducers and noise-monitoring algorithms, paradoxically highlight the acoustic workload traditionally managed by physical booths.[1]

This paper will first review the pertinent audiometric test environment standards covering the 125-8000 Hz range. Subsequently, it will characterize typical single-walled small audiometric booths. The core of the paper will present a compilation and analysis of sound attenuation data for these booths across the full spectrum, followed by an examination of an alternative boothless approach. Factors influencing achieved sound attenuation in practice, particularly concerning low-frequency performance, will then be discussed. Finally, conclusions will be drawn, and recommendations offered for selecting equipment suitable for the entire 125-8000 Hz audiometric range.

2. Audiometric Test Environment Standards for Occupational Screening

To ensure the accuracy and comparability of audiometric tests in occupational settings, national and international standards prescribe the maximum permissible ambient noise levels (MPANLs) within the test environment. These standards recognize that excessive background noise, across a wide range of frequencies, can elevate hearing thresholds, thereby invalidating test results. The primary role of an audiometric booth or an effectively attenuating headset in boothless systems is to reduce external ambient noise to levels at or below these specified limits for air conduction testing, covering the full audiometric range from 125 Hz to 8000 Hz, which is essential for comprehensive hearing assessment, even when primary monitoring focuses on the 500-8000 Hz range.

2.1 ANSI/ASA S3.1-1999 (R2018)

The American National Standard ANSI/ASA S3.1-1999 (R2018), "Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms," is a widely adopted standard in the United States.[1] It specifies MPANLs in decibels Sound Pressure Level (dB SPL) per octave or one-third octave band. These levels are designed to prevent threshold shifts greater than 2 dB for approximately 50% of listeners when pure tones are presented at reference equivalent hearing threshold levels (0 dB HL). For occupational hearing screening, which primarily focuses on air conduction thresholds, the MPANLs stipulated by ANSI S3.1 are critical across the entire measurement spectrum.

A key consideration within ANSI S3.1 is its explicit recognition of the impact of low-frequency noise on higher-frequency testing. The standard provides different MPANLs for testing, and even when the intended test frequency range for threshold determination begins at 500 Hz, ambient noise at lower frequencies (125 Hz and 250 Hz) must still be controlled due to the upward spread of masking.[1] This psychoacoustic phenomenon means that loud low-frequency sounds can make it harder to hear softer high-frequency sounds, effectively raising the hearing threshold at those higher frequencies. Therefore, controlling ambient noise at 125 Hz and 250 Hz is not merely an auxiliary concern but a requirement for valid testing from 500 Hz upwards.

The MPANLs also differ based on:

- **Transducer Type:** MPANLs differ for air conduction audiometry with ears covered (supra-aural or insert earphones). MPANLs are generally less stringent when using insert earphones due to their deeper insertion and better seal, providing more inherent attenuation.[1]
- **Minimum Test Level:** Standard MPANLs are for testing to 0 dB HL. If screening is performed at higher stimulus levels (e.g., 25 dB HL), the screening level can be arithmetically added to the 0 dB HL MPANL values, making requirements less stringent.[1] This adjustment, however, must be applied cautiously, ensuring that the underlying principle of achieving true thresholds is not compromised.

Table 2.1 provides a summary of ANSI S3.1-1999 (R2018) MPANLs for air conduction audiometry using supra-aural earphones when the intended test frequency range is 500-8000 Hz. These values, including those for 125 Hz and 250 Hz, represent a common target internal acoustic environment. The MPANL of 49 dB SPL at 125 Hz and 35 dB SPL at 250 Hz are particularly relevant for the expanded scope of this paper, as they set clear benchmarks for low-frequency noise control inside the test environment.[1]

Table 2.1: Summary of ANSI S3.1-1999 (R2018) MPANLs (dB SPL) for Air Conduction Audiometry (Ears Covered, TDH-type Supra-Aural Earphones, Test Range 500-8000 Hz).

Octave Band Center Frequency (Hz)	MPANL for Air Conduction (Supra-Aural, 500-8000 Hz Test Range) (dB SPL)
125	49
250	35
500	21
1000	26
2000	34
4000	37
8000	37

Source: Adapted from ANSI/ASA S3.1-1999 (R2018).[1] Note: MPANLs at 125 Hz and 250 Hz are specified to control upward spread of masking when testing begins at 500 Hz.

2.2 ISO 8253-1:2010

The international standard ISO 8253-1:2010, "Acoustics - Audiometric test methods – Part 1: Pure-tone air and bone conduction audiometry," also specifies maximum permissible ambient sound pressure levels (MPASPLs) for audiometric testing environments.[1] These MPASPLs are intended to ensure that hearing thresholds can be measured down to 0 dB HL with a maximum uncertainty of +2 dB due to ambient noise. While the provided documentation specifically mentions ISO 8253-1:2010 providing MPASPLs for "typical current supra-aural earphones" for the 500-8000 Hz test range, the full standard generally covers the audiometric frequencies from 125 Hz to 8000 Hz for air conduction audiometry. A provision exists within ISO 8253-1:2010 allowing for an 8 dB increase in the MPASPLs if a maximum uncertainty of +5 dB for the threshold value is deemed acceptable.[1] The implications of these provisions must be considered in the context of achieving valid thresholds across all frequencies, including 125 Hz and 250 Hz, as noise at these frequencies can still influence the overall test validity. The selection of appropriate MPASPLs under ISO guidelines should therefore account for the entire spectrum of potential ambient noise interference.

2.3 SANS 10182 (South Africa)

The South African National Standard SANS 10182, "The measurement and assessment of acoustic environments for audiometry," provides MPASPLs for audiometric testing environments within South Africa.[1] Like ISO 8253-1, SANS 10182 is understood to provide guidance for the full range of audiometric frequencies typically tested. A key practical aspect of SANS 10182 is its provision for adjusting these MPASPLs based on the specific sound attenuation characteristics of the headset employed (e.g., insert earphones vs. supra-aural earphones) and the minimum hearing level being targeted in the test protocol. For instance, if occupational health screening is performed at a level of 15 dB HL instead of 0 dB HL (as may be relevant for Percentage Loss of Hearing calculations under Instruction 171 in South Africa), the permissible ambient noise levels can be correspondingly higher.[1] This flexibility allows testing in slightly noisier environments than would be acceptable for 0 dB HL threshold testing, but careful consideration must be given to ensure that even with these adjustments, noise at 125 Hz and 250 Hz does not compromise the accuracy of tests at higher frequencies. SANS 10182 also specifies a method for manufacturers to determine MPASPLs for different headsets.[1]

The fundamental purpose of these standards is to create a test environment where an employee's true air conduction hearing capabilities can be assessed without interference from background noise across the entire 125-8000 Hz range. The explicit requirements by ANSI S3.1 for controlling 125 Hz and 250 Hz noise to prevent upward spread of masking, and the broader frequency coverage inherent in ISO and SANS standards, underscore the necessity of evaluating audiometric environments comprehensively, not just at the target test frequencies for hearing loss monitoring. This comprehensive approach is vital because uncontrolled low-frequency noise can lead to inaccurate audiograms, potentially masking early signs of hearing loss or, conversely, suggesting a loss where none exists at the tested frequencies.

3. Characterization of Typical Single-Walled Small Audiometric Booths for Occupational Screening

To analyze the attenuation performance of audiometric booths for occupational health, it is necessary to define what constitutes a "typical single-walled small" unit suitable for such applications. These characteristics directly influence the booth's ability to attenuate sound across the 125-8000 Hz spectrum, with low-frequency attenuation often being the most challenging aspect of their design.

3.1 Defining "Small"

The term "small" in the context of audiometric booths generally refers to enclosures designed for single-occupant use, primarily for hearing screening in clinical or industrial settings where space may be limited and portability might be a factor.[1] While a universal dimensional standard for "small" does not exist, manufacturer specifications typically indicate external dimensions in the order of 1 to 1.5 meters in width and depth, and around 2 to 2.5 meters in height. This investigation focuses on booths within this smaller, often demountable or portable, size category.[1] The limited internal volume of such booths can also influence the internal acoustic field, particularly at low frequencies.

3.2 Defining "Typical" Single-Walled Construction for Occupational Screening

"Single-walled" refers to the fundamental construction method of the booth's enclosure panels, meaning there is one primary layer of attenuating material in the walls, floor, and ceiling, as opposed to double-walled constructions which offer higher levels of isolation. Typical characteristics relevant to occupational screening include:

- **Panel Construction:** Modular panels are common, typically ranging from 63 mm to 100 mm in thickness. These often feature a steel outer shell for durability and mass, an acoustic infill material (such as high-density mineral wool, acoustic foam, or composite materials), and a perforated inner steel surface designed to absorb sound reflections within the booth, reducing reverberation.[1] The mass and damping characteristics of these panels are primary determinants of transmission loss, particularly at low to mid frequencies. Lighter constructions generally provide less attenuation at lower frequencies.
- **Doors and Windows:** Booths usually incorporate a single acoustic door, which is a critical component for overall sound attenuation. Effective sealing around the door perimeter is paramount, often achieved with magnetic compression seals or multiple gaskets. Windows are typically double-glazed with panes of different thicknesses or laminated acoustic glass to improve sound insulation and reduce coincidence dip effects.[1] Doors and windows often represent the acoustically weakest points in a booth's construction if not properly designed and sealed.
- **Ventilation:** Silenced ventilation systems are necessary to provide airflow without compromising acoustic integrity. These systems use attenuated air pathways, often incorporating baffles or acoustic lining to reduce noise transmission from the fan and the external environment.[1] The self-noise of the ventilation system must also be low enough not to interfere with audiometric testing.
- **Floor:** Floors are often isolated or vibration-dampened to reduce the transmission of structure-borne noise from the building into the booth. This can be achieved through resilient mounting, such as rubber skids, or by constructing a "floating floor".[1] Effective floor isolation is particularly important for attenuating low-frequency vibrations.
- **Portability and Assembly:** Many small single-walled booths are designed for ease of assembly and disassembly, featuring cam-locking systems or similar mechanisms to join panels. Some models may be equipped with casters for portability.[1] While convenient, these features can sometimes compromise acoustic seals if not engineered and maintained correctly.

The construction elements described above collectively determine the booth's sound attenuation capabilities. Achieving significant noise reduction, especially at lower frequencies like 125 Hz and 250 Hz, is challenging for single-walled structures due to the longer wavelengths of low-frequency sound and the typically limited mass and damping of such constructions compared to more substantial enclosures. Therefore, while a booth might be described as "single-walled," its actual performance across the full 125-8000 Hz range can vary considerably based on the quality of these design and construction details.

4. Global Review and Sound Attenuation Performance of Single-Walled Booths

This section provides an overview of various single-walled small sound booths suitable for occupational and diagnostic audiometry from different international markets. The primary function of these booths is to reduce ambient workplace or clinical noise to levels that permit accurate hearing assessment across the entire 125-8000 Hz range. The following tables compile manufacturer-specified data. Table 4.1 presents comprehensive specifications including dimensions and standards compliance, while Table 4.2 focuses specifically on sound attenuation (Noise Reduction in dB) across standard octave band frequencies, including 125 Hz and 250 Hz where data are available. These tables aim to provide a comparative basis for evaluating different models. It is important to note that the level of detail in publicly available specifications, particularly for low-frequency attenuation, can vary significantly between manufacturers.

Table 4.1: Comprehensive Comparison of International Single-Walled Small Sound Booths.

Manufacturer	Model	Country /Market	Ext. Dimensions (W×D×H, m)	Int. Dimensions (W×D×H, m)	Wall Thick. (mm)	Stated Standards Compliance	
Amtronix	AX2 High Performance Super Booth	South Africa	1.2×1.2×2.4	1.0×1.0×2.0	100	SANS 10182	[1]
ACTS CC	AVX1	South Africa	0.745×0.975×1.917	0.62×0.85×1.72	N/S (5 layers)	SANS 10182, ISO	[8]
ACTS CC	AVX2	South Africa	1.998×1.998×2.277	1.783×1.783×1.96	100 (5 layers)	SANS 10182, ISO	[2]
Eckel Acoustics	CL Single Wall	USA/Canada	N/S	N/S	N/S	N/S	
Eckel Acoustics	C Single Wall Standard	USA/Canada	N/S	N/S	N/S	N/S	
Eckel Acoustics	C Single Wall Advanced	USA/Canada	N/S	N/S	N/S	N/S	
Eckel Acoustics	H Single Wall	USA/Canada	N/S	N/S	N/S	N/S	
IAC Acoustics	40a Series (general)	UK/Europe/Global	Varies (e.g. 40a-1: 1.21×1.12×2.197)	Varies (e.g. 40a-1: 1.016×0.916×1.995)	102	ISO 8253, HTM 2045, ASTM E596	[11]
IAC Acoustics	AudioMetric Booth (e.g., 250/350 variant)	UK/Europe/Global	Varies (e.g. 0.737×0.991×1.918 for 252 model)	Varies (e.g. 0.610×0.864×1.676 for 252 model)	~63.5 (2.5″)	ISO 8253	[14]

ETS-Lindgren	RE-140/141	USA/Global	N/S	N/S	N/S	N/S	1
ETS-Lindgren	RE-142 Series (Single Wall)	USA/Global	N/S	N/S	N/S	N/S	1
ETS-Lindgren	RE-142 Series (Single Wall Enhanced)	USA/Global	N/S	N/S	N/S	N/S	
Whisper Room, Inc.	Standard Wall (STD) (Example MDL 4848 S)	USA	~1.27 x ~1.27 x ~2.11	N/S	N/S	ANSI (packages meet)	16
Amplivox (UK)	Model 250s	UK	0.73×0.99×1.945	0.604×0.86×1.68	N/S	ISO 8253-1	17
Waveform Acoustics (Australia)	Audiometric Mini Booth	Australia	N/S	N/S	N/S	N/S	
Puma Soundproofing	PRO30 (1x1 example)	Italy/Europe	1.07×1.07×2.44	0.92×0.92×2.01	75	EU 2017/745, ISO 8253-1	18
Puma Soundproofing	PRO40 SLIM (1x1 example)	Italy/Europe	1.07×1.00×2.27	0.95×0.90×2.00	50	EU 2017/745, ISO 8253-1	23
QuietStar	QS3	UK	2.2×1.2×2.21	2.0×1.16×2.0	N/S	ISO 8253	26
Kube Sound Isolation	Silver Series (1.0m x 1.0m example)	UK	1.0×1.0×2.1	N/S	80	N/S	28
SIBELMED	S-40 A	Spain (distr.)	0.90×0.90×2.13	0.77×0.77×1.90	N/S	CE Class (93/42/CEE)	30
HS Engineers	HSE-112 / HSE-AC001 (examples)	India	Varies (e.g. 1.2×1.2×2.4)	N/S	Up to 100	"Legal norms"	31
ESR Systems	ESR (general models)	India	Varies	N/S	100-200	"Legal norms"	33
ADF Industries	Micro Booth	Australia	1.05×0.81×2.0 (on castors)	N/S	N/S	AS/NZS 1269.4	34
NCS Acoustics	Medium Booth	New Zealand	1.42×1.2×2.29	N/S	N/S	"Hearing testing practice	37

						stds"	
Gzrisound	LTE-MSL Mobile	China	1.2×1.2×2.3	1.0×1.0×2.0	~60	GB/T16403	39
Melison	Mobile Booth / DM1212	China	Mobile: 0.89×0.76×2.03 / DM1212: 1.2×1.2×2.18 (unassembled)	Mobile: 0.80×0.60×1.76/ DM1212: 1.07×1.07×1.9	N/S	GB/T16403, ISO13485 factory	43

N/S: Not Specified in reviewed documentation. Dimensions are approximate where converted or inferred. Wall thickness may vary or be part of a composite structure. Reference numbers are based on the main reference list in Section 9.

Table 4.2: Manufacturer-Specified Noise Reduction (dB) for Selected Single-Walled Audiometric Booths (125-8000 Hz).

Manufacturer	Model/Series Name	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Amtronix	AX2 High Performance Super Booth	27.8	27.8	34.3	45.5	53.3	59.1	58.0
Eckel Acoustics	CL Single Wall	19	30	39	50	58	59	N/A
Eckel Acoustics	C Single Wall Standard	24	32	44	53	58	61	N/A
Eckel Acoustics	C Single Wall Advanced	31	44	57	63	68	67	N/A
Eckel Acoustics	H Single Wall	28	36	46	53	58	62	N/A
IAC Acoustics	40a Series	25	37	48	55	59	61	62
IAC Acoustics	AudioMetric Booth (e.g., 250/350 variant)	18	32	38	44	51	52	50
ETS-Lindgren	RE-140/141	27	37	44	53	58	60	62
ETS-Lindgren	RE-142 Series (Single Wall)	24	32	42	49	55	57	55
ETS-Lindgren	RE-142 Series (Single Wall Enhanced)	26	32	43	50	57	59	58
Whisper Room, Inc.	Standard Wall (STD) (Example Data)	21	22	23	23	23	27	N/A
Amplivox	Model 250s	18	32	38	44	51	52	50

Waveform Acoustics	Audiometric Mini Booth	20	25	30	35	40	45	N/A
ACTS CC	AVX1	19.9	24.0	29.0	41.1	49.0	55.5	52.3
ACTS CC	AVX2	27.0	26.8	35.1	44.9	53.9	58.7	59.0
Puma Soundproofing	PRO30	23.4	24.1	27.8	34.5	31.3	36.4	37.7

N/A indicates data not available in the reviewed sources for that specific frequency. Data sourced from references listed in Table 4.1 and.[1]

The data presented in Table 4.2 form the basis for the comparative analysis in the subsequent section. It is evident even from a cursory review that reported noise reduction values, particularly at the lower frequencies of 125 Hz and 250 Hz, exhibit considerable variation among different models. This initial observation underscores the importance of scrutinizing model-specific data rather than relying on generic categorizations like "single-walled booth."

5. Comparative Analysis of Sound Attenuation Performance

Using the compiled manufacturer-specified noise reduction data from Table 4.2, the average, minimum, and maximum attenuation values at each octave band frequency from 125 Hz to 8000 Hz were calculated. These summary statistics provide an overview of the performance spectrum for typical single-walled audiometric booths across the key range for comprehensive occupational hearing screening.

Table 5.1: Summary of Calculated Attenuation Characteristics (Noise Reduction, dB) for Single-Walled Audiometric Booths (125-8000 Hz).
(Based on data from Table 4.2 for models with available data at each frequency)

Statistic	125 Hz (n=16)	250 Hz (n=16)	500 Hz (n=16)	1000 Hz (n=16)	2000 Hz (n=16)	4000 Hz (n=16)	8000 Hz (n=11)
Average Attenuation	23.7	30.7	38.5	45.2	49.7	53.5	54.7
Minimum Attenuation	18	22	23	23	23	27	37.7
Maximum Attenuation	31	44	57	63	68	67	62

Observations from the Data (125-8000 Hz):

The analysis of the compiled data across the full 125-8000 Hz range reveals several key characteristics pertinent to the selection and use of single-walled audiometric booths for occupational screening:

- **Frequency Dependence:** Sound attenuation generally increases with frequency. The average attenuation improves from 23.7 dB at 125 Hz and 30.7 dB at 250 Hz, to 38.5 dB at 500 Hz, and continues to rise to 54.7 dB at 8000 Hz (for the subset of booths with 8000 Hz data). This trend is consistent with the general acoustic principle that it is more challenging for structures of limited mass and complexity to attenuate lower frequency sound, which has longer wavelengths and can more easily cause structural vibration or find leakage paths.

- **Performance Range and Variability:** A significant range exists between the minimum and maximum reported attenuation values at each frequency, and this variability is particularly pronounced at lower frequencies.
  - At 125 Hz, the range is 13 dB (from 18 dB to 31 dB).
  - At 250 Hz, the range widens to 22 dB (from 22 dB to 44 dB).
  - At 500 Hz, the range is 34 dB (23 dB to 57 dB).
  - At 1000 Hz, the range is 40 dB (23 dB to 63 dB). This substantial variability underscores that the term "single-walled booth" encompasses a wide spectrum of acoustic performance capabilities. The wider relative variability at lower frequencies suggests that design and construction quality play an even more critical role in determining low-frequency sound insulation. Some manufacturers may invest more in features that enhance low-frequency performance (e.g., heavier panels, more robust seals), while others may prioritize portability or cost, leading to poorer low-frequency attenuation.
- **Low-Frequency Performance (125 Hz and 250 Hz):** The average attenuation values of 23.7 dB at 125 Hz and 30.7 dB at 250 Hz are considerably lower than those achieved at mid and high frequencies. The minimum reported values at these frequencies (18 dB at 125 Hz, 22 dB at 250 Hz) indicate that some booths offer very modest low-frequency isolation. Achieving the ANSI S3.1 MPANL of 49 dB SPL at 125 Hz and 35 dB SPL at 250 Hz (for supra-aural earphones, testing 500-8000 Hz) would require very quiet external ambient conditions if using a booth with such minimal attenuation. For example, with only 18 dB of attenuation at 125 Hz, the external noise would need to be below 49+18=67 dB SPL to meet the internal MPANL. In many industrial or urban environments, ambient noise at 125 Hz can easily exceed this level. This highlights a potential vulnerability in relying on some single-walled booths in environments with significant low-frequency noise.
- **Mid to High-Frequency Performance:** At frequencies of 500 Hz and above, the attenuation provided by most models improves significantly. However, even at these frequencies, the minimum performance observed (e.g., 23 dB at 500 Hz, 1000 Hz, and 2000 Hz; 27 dB at 4000 Hz) is substantially lower than the top performers (maximums of 57 dB to 68 dB). This indicates that even in the traditional range of focus, considerable differences exist.
- **Performance Boundaries:** Certain compact or more basic screening booths (e.g., WhisperRoom Standard Wall, Waveform Audiometric Mini Booth, Puma PRO30 based on their data in Table 4.2) tend to define the lower boundary of attenuation performance, especially at lower frequencies. Conversely, more robustly constructed single-wall models (e.g., Eckel C Single Wall Advanced, IAC 40a Series, Amtronix AX2) generally represent the higher end of single-wall performance across a broader spectrum. The number of manufacturers providing data for 125 Hz and 250 Hz (n=16 in this compilation for these frequencies, compared to n=11 for 8000 Hz) is substantial, yet the absence of this data from some models in broader catalogues could indicate either poorer performance that manufacturers choose not to highlight, or a historical focus on higher frequencies. This lack

of universal reporting for low frequencies can be a challenge for end-users needing comprehensive data.

The average attenuation values, when considered alongside MPANLs (Table 2.1), provide a general indication of potential suitability. For example, with an average attenuation of approximately 30.7 dB at 250 Hz and an MPANL of 35 dB SPL, an "average" booth might be adequate if external noise at 250 Hz does not exceed approximately 35+30.7=65.7 dB SPL. If screening is performed at 25 dB HL, this tolerance increases, as the MPANL can be adjusted upwards. However, reliance on average figures can be misleading. The minimum performance values observed necessitate much quieter external conditions or the selection of higher-performing booths, especially if low-frequency ambient noise is substantial and 0 dB HL testing is required. The significant spread between minimum and maximum performance at all frequencies, and particularly at 125 Hz and 250 Hz, reinforces the critical need for end-users to obtain and evaluate model-specific attenuation data across the entire frequency range of concern (125-8000 Hz) relative to their specific site noise conditions.

6. Factors Influencing Achieved Sound Attenuation

Manufacturer-specified attenuation values, such as those presented in Table 4.2, are typically obtained under controlled laboratory conditions according to standards like ASTM E596.[1] However, the actual noise reduction achieved in real-world field installations can be significantly different and often lower. Several factors influence this performance across the 125-8000 Hz range, with low-frequency attenuation being particularly susceptible to degradation. Understanding these factors is crucial for selecting appropriate equipment and ensuring its effective use.

- **Booth Design and Construction:**
  - **Wall Panel Integrity:** The thickness, mass, material composition (e.g., steel, gypsum, specialized acoustic cores), and damping of the wall, floor, and ceiling panels are fundamental to their sound transmission loss characteristics.[1] Heavier, more rigid panels generally offer better low-frequency attenuation. The integrity of panel joints is also critical; small gaps or weaknesses can compromise isolation.
  - **Seals:** Effective acoustic seals around doors, windows, ventilation pass-throughs, and jack panels (for connecting audiometric equipment) are paramount.[1] Air gaps are a primary cause of sound leakage, and their impact is often more pronounced for mid and high frequencies, but significant leaks will degrade low-frequency performance too. Degraded seals (e.g., hardened or compressed foam, damaged gaskets) are common maintenance issues that can severely reduce a booth's effective attenuation.[1] Continuous magnetic seals or multiple compressible bulb seals on doors are generally preferred.
  - **Doors and Windows:** Doors and windows are often the acoustically weakest points in a booth's construction due to their lower mass compared to walls and the complexities of sealing them effectively.[1] The mass of the door, the type of glazing (e.g., laminated acoustic glass, double glazing with an air gap), and the quality of the seals around the frame are critical. Lightweight doors or single-pane windows will significantly limit overall attenuation, especially at lower frequencies.

- **Ventilation Systems:** Ventilation systems must be designed with acoustic attenuators (silencers) to prevent noise from the fan or the external environment from entering the booth via the air ducts.[1] The self-noise generated by the ventilation fan itself must also be below the MPANLs for the test room.[1] Poorly designed or unattenuated ventilation paths can be a major source of noise intrusion, particularly for low-frequency rumble.
- **Jack Panels/Cable Pass-Throughs:** Openings for cables must be meticulously sealed. Specialized jack panels with sealed connectors or properly packed cable transits are necessary to maintain acoustic integrity.[1]
- **Floor Isolation:** Reducing structure-borne noise transmission from the building (e.g., footsteps, machinery vibration) is important, especially for low frequencies. This can be achieved using resilient mounts like rubber skids, vibration isolation pads, or by constructing a "floating floor" that is mechanically decoupled from the main structure.[1]

- **Installation Quality:**
  - **Proper Assembly:** Precise assembly of modular booths according to manufacturer instructions is crucial to ensure all seals are compressed correctly and there are no flanking paths (indirect sound transmission routes).[1] Misaligned panels or improperly tightened cam-locks can create small gaps that degrade performance.
  - **Site Preparation:** The booth should be installed on a level, solid surface to ensure proper seating and even compression of floor seals.[1] Uneven floors can lead to gaps and compromise isolation. The acoustic properties of the host room can also influence the perceived noise reduction.
- **Environmental Conditions:**
  - **External Noise Spectrum:** The characteristics of the ambient noise outside the booth significantly impact the internal noise levels. Environments with high levels of low-frequency noise (e.g., from HVAC systems, traffic, nearby machinery) pose a greater challenge for achieving MPANLs inside the booth, as low-frequency noise is inherently harder to attenuate.[1] Furthermore, such low-frequency noise can cause upward spread of masking, potentially affecting the accuracy of thresholds measured at higher frequencies, even if the low-frequency noise itself is not directly being tested.[1] Electrical hum from nearby equipment can also be a factor if not properly shielded or isolated.[1]
  - **Discrepancy Lab vs. Real-World:** It is widely recognized that laboratory-specified attenuation data may not be fully replicated in field installations due to the variables in installation quality, the specific acoustic environment of the host room, and potential flanking transmission paths not present in idealized lab setups.[1] This discrepancy can be more significant for low frequencies.
- **Field Verification:** Given the potential for divergence between specified and achieved performance, post-installation acoustic verification (often termed booth certification) is critical. This involves measuring the actual noise reduction provided by the installed booth across the relevant frequency range (125-8000 Hz) and comparing the internal ambient noise levels against the required MPANLs.[1] This step ensures that the booth, as installed in its specific location, provides a compliant testing environment.

Failure to address these factors can lead to an audiometric testing environment that does not meet the required standards, potentially invalidating test results, particularly when significant low-frequency ambient noise is present. Regular inspection and maintenance, especially of seals and ventilation components, are also essential to preserve the booth's acoustic performance over time.

7. Alternative Approaches: Boothless Audiometry for Occupational Screening

While traditional sound-attenuating booths are a common solution for creating controlled acoustic environments, boothless audiometry systems are emerging as a viable alternative, particularly valued for their increased portability and flexibility in various testing scenarios.[1] These systems aim to achieve the necessary noise reduction directly at the listener's ears, across the full 125-8000 Hz audiometric range.

7.1. Introduction to Boothless Audiometry

Boothless audiometry typically involves the use of specialized headsets that integrate sound transducers (earphones) with significant passive sound attenuation capabilities. These headsets are designed to physically block out external noise. A key feature of many advanced boothless systems is active ambient noise monitoring, often via a microphone integrated into the headset. This system continuously measures the noise levels near the ear. If the ambient noise exceeds permissible limits for accurate testing at a given frequency and intensity, the system can alert the operator or automatically pause the test until conditions improve.[1] This combination of passive attenuation and active monitoring is designed to ensure that hearing thresholds can be measured accurately even outside of a traditional sound booth, provided the ambient noise levels are within the operational limits of the device.

7.2. The Kuduwave Audiometer System

The Kuduwave audiometer, manufactured by GeoAxon, is an example of such a boothless system. It integrates the audiometer electronics directly with a headset that provides substantial sound-attenuating properties. This is achieved through circumaural earcups combined with insert earphones, a design referred to as Ambi-Dome technology by the manufacturer. The specified air conduction sound attenuation characteristics for the Kuduwave system across the 125-8000 Hz range are as follows [1]:

- 125 Hz: 31.0 dB
- 250 Hz: 37.7 dB
- 500 Hz: 43.8 dB
- 1000 Hz: 40.8 dB
- 2000 Hz: 38.1 dB
- 4000 Hz: 52.3 dB
- 8000 Hz: 45.8 dB

A critical feature of the Kuduwave system is its capability for continuous in-test ambient noise monitoring. This system is designed to optionally pause the audiometric test if the noise levels detected by its integrated microphone exceed the limits deemed acceptable for testing down to 0 dB HL under specific ambient noise conditions.[1] This active management of ambient noise interference is a significant departure from the purely passive attenuation offered by traditional booths.

7.3. Comparative Context for Occupational Screening

The passive sound attenuation offered by the Kuduwave headset can be compared to the average performance of the single-walled audiometric booths analyzed in Table 5.1. This comparison provides context for understanding its passive isolation capabilities.

Table 7.1: Comparison of Kuduwave Attenuation with Average Single-Walled Booth Attenuation (dB) (125-8000 Hz).

Octave Band Center Frequency (Hz)	Kuduwave Attenuation (dB)	Average Single-Walled Booth Attenuation (dB) (from Table 5.1)	Difference (Kuduwave - Average Booth) (dB)
125	31.0	23.7	**+7.3**
250	37.7	30.7	**+7.0**
500	43.8	38.5	**+5.3**
1000	40.8	45.2	**-4.4**
2000	38.1	49.7	**-11.6**
4000	52.3	53.5	**-1.2**
8000	45.8	54.7	**-8.9**

The comparison in Table 7.1 reveals that the Kuduwave system's specified passive attenuation is notably higher than that of the average single-walled booth at the lower frequencies of 125 Hz (+7.3 dB), 250 Hz (+7.0 dB), and 500 Hz (+5.3 dB). This suggests a strong passive capability for reducing low-frequency ambient noise. However, for frequencies from 1000 Hz to 8000 Hz, the average single-walled booth (as defined by the models in Table 4.2) offers higher passive attenuation.

It is crucial to interpret these passive attenuation figures in conjunction with the Kuduwave's active noise monitoring feature. While its passive attenuation may be lower than an average booth at higher frequencies, the system's ability to detect and react to excessive ambient noise provides an additional layer of quality control that is not inherent in passive booths. For environments with significant or unpredictable low-frequency noise, where average booths may struggle (average attenuation of 23.7 dB at 125 Hz and 30.7 dB at 250 Hz), the Kuduwave's superior passive low-frequency attenuation combined with active monitoring could offer a more reliable testing environment. Studies have suggested that the Kuduwave can yield reliable hearing thresholds comparable to those obtained with conventional audiometry, provided that ambient noise is adequately managed by its systems.[1] The choice between a boothless system and a traditional booth will therefore depend on the specific noise environment, the required level of attenuation across the full 125-8000 Hz spectrum, portability needs, and the value placed on active noise monitoring versus purely passive isolation. The "average single-walled booth" is a statistical construct; individual booth models may perform better or worse than this average, and direct comparison with specific models is always advisable.

8. Conclusion and Recommendations for Occupational Hearing Screening

This review of sound attenuation performance for single-walled audiometric booths and the Kuduwave boothless system underscores the complexities involved in selecting and implementing appropriate audiometric testing environments for occupational hearing screening. The data clearly demonstrate that achieving adequate noise reduction, particularly at lower frequencies (125 Hz and 250 Hz), is a significant challenge that requires careful consideration.

A critical distinction lies in how these systems address ambient noise. Traditional sound booths rely solely on passive attenuation; they do not inherently monitor the noise levels *inside* the booth during testing. This means that if external noise conditions change or if the booth's seals degrade over time, the internal ambient noise could exceed permissible levels without the operator's immediate knowledge, potentially compromising test validity. Ideally, a sound booth would incorporate an internal sound level meter (SLM) to provide real-time feedback on the acoustic environment, similar to the active monitoring capabilities of systems like the Kuduwave. This lack of active internal monitoring in standard booths places a greater onus on initial setup, regular verification, and maintenance to ensure ongoing compliance.

Summary of Findings:

- **Single-Walled Booth Attenuation:**
  - Average attenuation for single-walled booths (based on the analyzed sample) ranges from approximately 23.7 dB at 125 Hz and 30.7 dB at 250 Hz, increasing to 38.5 dB at 500 Hz and up to 54.7 dB at 8000 Hz (Table 5.1).
  - A substantial performance range exists at all frequencies. Minimum attenuation values can be as low as 18 dB at 125 Hz, 22 dB at 250 Hz, and 23 dB between 500-2000 Hz. Maximum values can reach 31 dB (125 Hz), 44 dB (250 Hz), and up to 68 dB (2000 Hz) (Table 5.1). This wide variability, especially at low frequencies, highlights that not all single-walled booths are acoustically equivalent.
- **Kuduwave Boothless System Attenuation:**
  - The Kuduwave system specifies passive attenuation of 31.0 dB at 125 Hz, 37.7 dB at 250 Hz, 43.8 dB at 500 Hz, declining to 38.1 dB at 2000 Hz, then increasing to 52.3 dB at 4000 Hz, and 45.8 dB at 8000 Hz.[1]
  - Crucially, this passive attenuation is supplemented by an active ambient noise monitoring system designed to pause testing if noise exceeds permissible limits.
- **Performance Relative to Standards (e.g., ANSI S3.1):**
  - The suitability of any system depends heavily on the external ambient noise levels across the entire 125-8000 Hz spectrum and the specific screening protocol (e.g., target HL for testing, transducer type).

    - For 0 dB HL screening with supra-aural earphones in environments with significant low-frequency noise (e.g., exceeding 60-70 dB SPL at 125 Hz or 55-65 dB SPL at 250 Hz), many single-walled booths, particularly those at the lower end of the performance spectrum, may be challenged to meet MPANLs (e.g., 49 dB SPL at 125 Hz, 35 dB SPL at 250 Hz internally per ANSI S3.1 for 500-8000 Hz testing). Higher-performing booth models or boothless systems with robust passive low-frequency attenuation and active noise monitoring may be necessary in such conditions. The upward spread of masking from uncontrolled low-frequency noise remains a critical concern for test validity even when primary interest is in higher frequencies.
- **Implications for Equipment Selection:**
    - The designation "single-walled booth" is not a uniform guarantee of acoustic performance. Significant differences exist between models, especially in their ability to attenuate low-frequency sound.
    - Selection requires a thorough assessment of site-specific ambient noise conditions across the 125-8000 Hz range and careful consideration of the audiometric test protocols to be used. Relying solely on manufacturer claims for mid-to-high frequencies without scrutinizing low-frequency data can lead to inadequate attenuation where it is critically needed.

Recommendations:

To ensure accurate and reliable audiometric testing in occupational settings, the following recommendations are made:

1. **Scrutinize Manufacturer Data:** End-users should request and carefully evaluate detailed, octave-band specific Noise Reduction (NR) or Transmission Loss (TL) data from manufacturers across the *entire 125-8000 Hz frequency range*. Do not assume adequate low-frequency performance if only mid-to-high frequency data is provided.
2. **Conduct Comprehensive Site Noise Surveys:** Before selecting or installing any audiometric testing solution, measure and analyze the ambient noise levels at the proposed testing location(s) across all octave bands from *125 Hz to 8000 Hz*. This survey should capture typical worst-case noise conditions.
3. **Specify Based on Need and Full Spectrum Analysis:** Determine the required MPANLs based on the chosen transducers (e.g., supra-aural vs. circum-aural earphones), the minimum hearing level to be tested (e.g., 0 dB HL or a screening level), and the applicable standards (e.g., ANSI S3.1, ISO 8253-1, SANS 10182). Calculate the required attenuation by subtracting the target internal MPANL from the measured external ambient noise at each frequency across the 125-8000 Hz range.
4. **Prioritize Initial and Ongoing Acoustic Verification:** For audiometric booths, conduct post-installation field testing (initial booth certification) to verify that the achieved attenuation meets specifications and that internal ambient noise levels comply with MPANLs across the *full 125-8000 Hz spectrum*. Furthermore, this certification must preferably be conducted on an annual basis to ensure the booth continues to meet the MPANL requirements for the specific headset being used and the relevant standard (e.g., ANSI, ISO, SANS). This verification is a critical quality control step to ensure ongoing compliance. For

boothless systems, diligently utilize the active noise monitoring features and understand their operational limits relative to the site's noise conditions. In the case of portable or mobile units with built in booths it is recommended to verify the booth more often due to the inherent risk of booth attenuation failure due to movement.

5. **Maintain Equipment Integrity:** Regularly inspect and maintain all components of the audiometric testing environment. For booths, this includes checking the integrity of door seals, window seals, panel joints, and ventilation silencers, as these are critical for maintaining acoustic performance, especially against low-frequency noise.[1] For boothless systems, ensure earphone cushions and headset components are in good condition.

Limitations: This review is based on publicly available manufacturer-specified data, which are typically obtained under laboratory conditions. Real-world performance can differ due to installation variables, flanking paths, and the specific acoustic characteristics of the host environment.

In conclusion, the selection and verification of audiometric testing environments demand a careful, evidence-based approach that considers the full 125-8000 Hz frequency spectrum. The significant variability in performance, especially at low frequencies, and the inherent lack of active internal noise monitoring in most traditional sound booths, mean that occupational health professionals must move beyond generic labels. They must engage in detailed evaluation of equipment specifications against site-specific needs and commit to regular, rigorous verification to ensure the validity of hearing conservation programs.

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