Bone Conduction Audiometry The Good, The Bad and The Interesting

"my bone calibration is off"

Sherman G. Lord, Au.D.
e3 Midlantic Technologies Group
slor@midlantictech.com

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What are the Goals of this presentation?

1. To increase your confidence in measured BC thresholds when they don't seem to make sense.

2. To discourage "tampering" with the measured BC thresholds when the results don't confirm to "the way it is supposed to be" (Studebaker 1962)

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Learning objectives

After this course participants will be able to:

1. Describe at least two technical variables affecting bone conduction audiometry.
2. Describe calibration variables in bone conduction audiometry.
3. Describe the difference between forehead and mastoid placement of the bone oscillator and determine the best placement for his/her patient

3

Topics

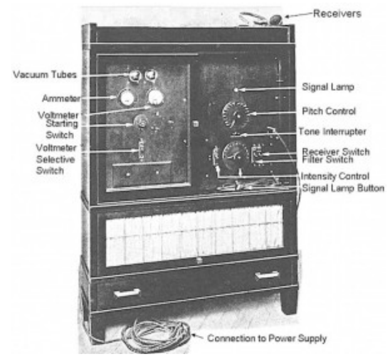
- Brief history of audiometric BC testing
- How we hear by BC
- Calibration of BC vibrators
- Variables affecting BC threshold measurement
- Positive and negative air/bone gaps
- Mastoid or forehead placement

4

History

Electronic instruments in medicine

- First audiometer 1919 in Germany
- First US made audiometer was in 1922 from Western Electric
  - A much smaller version soon became available (1923)
- Bone conduction was added to the device in 1928
- Reference levels for normal hearing not established until 1936
- First standard for audiometer calibration came in 1951 (ASA now ANSI) – air only



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How we hear by bone conduction

News flash… when a BC oscillator is placed at any location on the skull, it causes vibration of the temporal bones and stimulates both cochleas.

Of course, you already knew that

- Unlike hearing via the AC pathway, BC hearing is much more complex
- Three modes of bone conduction hearing
  - Compression/distortion
  - Inertial
  - Osseotympanic
- Each contribute to BC hearing in a unique way affecting different frequency regions

Many physicians expect BC thresholds to equal air in the absence of a confirmed ME disorder

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Compression/Distortion Mode

- Vibration of the skull compresses the otic capsule
- This causes distortion within the cochlear fluids and movement of the basilar membrane
- Occurs as a result of pressure differentials at the round window, vestibule, and semicircular canals
- This mode contributes to BC hearing in the high frequency range (>1.5KHz)

This is the only mode of BC hearing that DOES NOT involve the AC pathway

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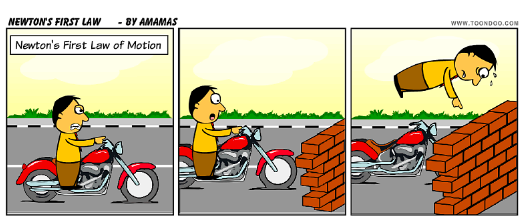
Inertial mode

- Newton's first law of motion
- Involves the contribution of the ossicular chain to BC hearing
- At low frequencies (<1.5KHz) the skull moves as a rigid body
- Since the ossicles are loosely coupled to the skull, they lag behind the skull when it is vibrated
- As a result , the stapes footplate vibrates in the oval window
  - Creates a traveling wave



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Osseotympanic mode

- Another non-cochlear influence on BC hearing
- Due to occlusion effect when testing bone anc masking the non-test ear
- Skull vibration causes the ear canal walls to vibrate
- The normal AC hearing pathway is then activated
- Dominant in the low frequencies
- Not an issue when ears are not occluded during BC testing


A


B

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Modes of BC Hearing – Bottom Line

- Bone conduction hearing levels are affected by non-cochlear sources using the air conduction pathways
- Vibration of the skull during BC testing does not totally bypass the external and middle ears

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Audiometer calibration

- Voluntary standards are published by ANSI and ISO
  - Only required if written into a state or federal law
- Periodically reviewed by an appointed working group
  - The standard is either revised, reaffirmed or withdrawn
- Made up of industry representatives; very few clinicians
- International uniformity in the standard since the early 90's

Audiometer calibration

Air conduction

- Supra-aural
  - TDH 39; TDH-49/50; DD45
- Circumaural
  - HDA200/300; DD450; HDA280; Koss HV/1A
- Insert earphones
  - ER3A; ER3C; IP30; EARTone 3A

All have different RETSPLs and may require a different calibration test coupler

Table 5 — Reference equivalent threshold sound pressure levels (RETSPLs) (dB re 20µPa) for supra-aural earphones in common use

Frequency	Supra-aural earphones			
	Earphone type[a]	TDH 39	TDH 49/50	DD45
Hz	IEC 60318-1	NBS 9A / IEC 60318-3		
125	45.0	45.0	47.5	47.5
160	38.5	37.5		40.5
200	32.5	31.5		33.5
250	27.0	25.5	26.5	27.0
315	22.0	20.0		22.5
400	17.0	15.0		17.5
500	13.5	11.5	13.5	13.0
630	10.5	8.5		9.0
750	9.0	7.5	8.5	6.5
800	8.5	7.0		6.5
1000	7.5	7.0	7.5	6.0
1250	7.5	6.5		7.0
1500	7.5	6.5	7.5	8.0
1600	8.0	7.0		8.0
2000	9.0	9.0	11.0	8.0
2500	10.5	9.5		8.0
3000	11.5	10.0	9.5	8.0
3150	11.5	10.0		8.0
4000	12.0	9.5	10.5	9.0
5000	11.0	13.0		13.0
6000	16.0	15.5	13.5	20.5
6300	21.0	15.0		19.0
8000	15.5	13.0	13.0	12.0
Speech	20.0	19.5	20.0	18.5

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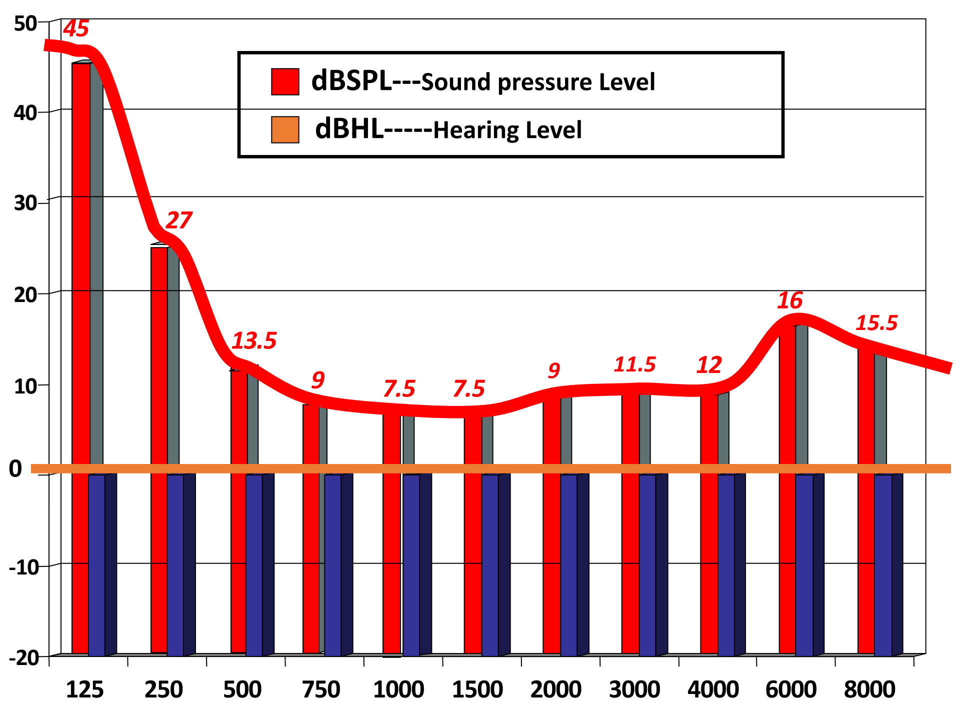

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Supra-aural headphone
NBS-9A 6cc coupler

Insert phone calibration
HA-2 coupler – 2cc coupler

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Audiometer calibration

Bone conduction

- Standard for BC first published (ANSI-1972)
  - Based on Beltone 5A artificial mastoid
- ANSI-1981 issued revised standards
  - Based on the B&K 4930
- Revised again in 1996 – unchanged since
- Force level is the reference, not SPL
- Calibration values reported in RETFLs (Reference Equivalent Threshold Force Levels)
  - BC vibrator force changed to an electrical signal
- Couplers are temperature and humidity sensitive

Recent findings bring into question the accuracy of the RETFL at 4KHz
Margolis et al (2013)
Altus et al (2018)
Margolis (2019)

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Table 8 — Reference equivalent threshold force levels (RETFLs) for bone vibrators

Frequency (Hz)	Mastoid (dB re 1 μN)	Forehead (dB re 1 μN)	Forehead minus mastoid
250	67.0	79.0	12.0
315	64.0	76.5	12.5
400	61.0	74.5	13.5
500	58.0	72.0	14.0
630	52.5	66.0	13.5
750	48.5	61.5	13.0
800	47.0	59.0	12.0
1000	42.5	51.0	8.5
1250	39.0	49.0	10.0
1500	36.5	47.5	11.0
1600	35.5	46.5	11.0
2000	31.0	42.5	11.5
2500	29.5	41.5	12.0
3000	30.0	42.0	12.0
3150	31.0	42.5	11.5
4000	35.5	43.5	8.0
5000	40.0	51.0	11.0
6000	40.0	51.0	11.0
6300	40.0	50.0	10.0
8000	40.0	50.0	10.0
Speech	55.0	63.5	8.5

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Key Point

ANSI and ISO bone conduction values were obtained with 40dB EM in the contralateral ear.
The standard assumes that a contralateral masking signal will be applied when performing clinical measurement of bone conduction thresholds.

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B&K 4930 Artificial Mastoid

Larson-Davis AMC493

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Variables that may affect bone conduction thresholds and the air/bone gap

- Positioning of the BC vibrator on the mastoid process
- BC vibrator surface area
- Application force
- Occlusion effect
- Accurate air conduction thresholds
- Reference threshold levels and a normal distribution

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Positioning of the BC oscillator

- On the bony mastoid prominence
- Should not be placed on hair
- Should not be touching the pinna
- Tab of headband on contralateral temple region
  - Ensures stability
- For smaller heads, may need to wrap top of headband

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BC oscillator surface area

- B71 and B81 have a disk "protrusion"
- Contact/surface area is 175mm on B71 and B81
- Current models designed for uniformity across subjects
- Make sure as much of the disk surface area as possible contacts the mastoid
- Greater contact area yields better thresholds

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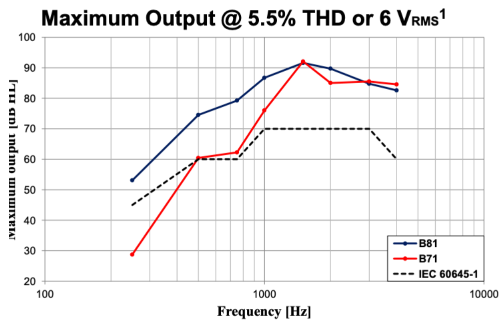
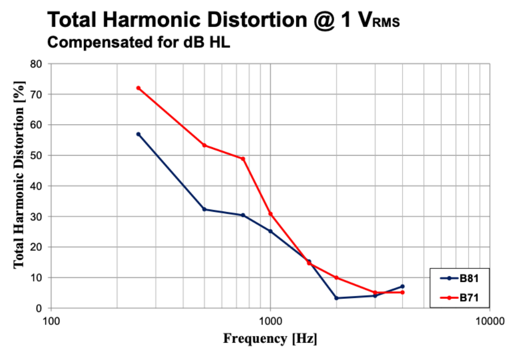


Radioear B-81



- Higher maximum output
  - 250Hz – 1KHz
- Lower distortion in LFs
  - 25% less at 250Hz
  - 5% less at 500Hz and 1KHz

Application force

- BC headband static force of 5.4N +/-0.5 when spread to 145 mm
  - This equals a pressure of 510 grams
- Studebaker (1962) measured the force of a BC headband on the mastoid at 322 g with a range of 142 grams
- Toll, Emanuel, & Letowski (2011) found mean thresholds within ±2dB across a range of static force levels (2.4N – 5.4N)
- Application force level appears to interact differentially across both frequency and vibrators (Dirks & Kamm 1975)
- Force level appears to have little effect on the reliability of BC thresholds

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TABLE 5. Physical output in dB re 1 dyne for the B-70A and B-71 bone vibrators at static forces of 3.4 N and 5.4 N and differences in dB between the two force conditions. Measurements were made on the Bruel and Kjaer 4930 artificial mastoid with 0.1 v at vibrator terminals.

		Frequency in k Hz				
Vibrator	*Force (N)*	*0.25*	*0.50*	*1.0*	*2.0*	*4.0*
B-70A	5.4	69.0	83.9	78.8	69.6	54.2
	3.4	69.0	82.9	77.3	68.6	53.6
	5.4 minus 3.4	0.0	1.0	1.5	1.0	0.6
B-71	5.4	74.5	83.3	77.2	71.0	66.2
	3.4	74.4	81.3	76.2	69.2	65.4
	5.4 minus 3.4	0.1	2.0	1.0	1.8	0.8

Dirks and Kamm 1975

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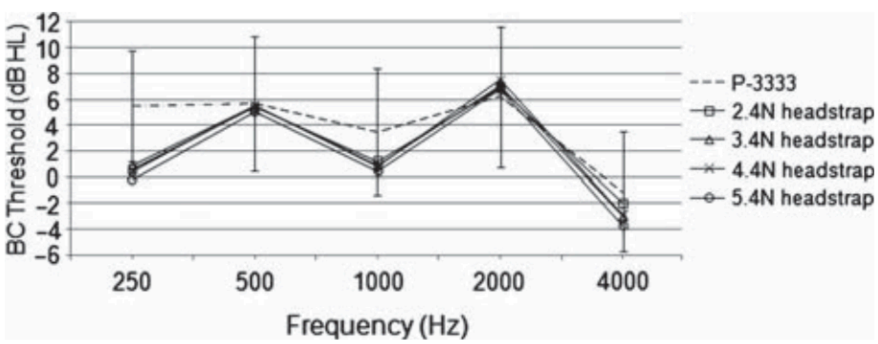

Figure 1. Mean BC thresholds as a function of frequency for each static force compared with P-3333 results for the test condition. Error bars represent ± 1 SD for P-3333.

Toll, Emanuel, Letowski 2011

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Occlusion effect

- LF acoustic energy is "trapped" in the occluded ear
  - The trapped LF acoustic energy increases the SPL delivered to the cochlea
    - Osseotympanic mode
- Enhancing the measured hearing threshold (125Hz- 1KHz)
- Style of AC transducer affects the amount of OE
  - Supra-aural earphones create the largest OE
  - Insert phones with shallow insertion similar to SA
  - Circumaural, very little except at 250Hz
- Not present in CHL of 20dB or more

Occlusion effect values for SA phones

250Hz 30dB
500Hz 20dB
1KHz 10dB

Occlusion effect values for IE (deep insertion)

250Hz 10dB
500Hz 10dB
1KHz 0dB

Occlusion effect values for CA phones

250Hz 10dB
500Hz 0dB
1KHz 0dB
(Margolis & Moore 2011)

Yacullo 2009

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Table 1. Acoustic and psychoacoustic occlusion effects for six adult subjects. Occlusion effects were measured for insert earphones (Etymotic Research ER3) with full insertion (F) and partial insertion (P), circumaural earphones (Sennheiser HDA 200), and supra-aural earphones (Telephonics TDH-50 with Type 51 cushion).

Frequency (kHz)		0.25	0.5	0.75	1.0	1.5	2.0	3.0	4.0	6.0
Earphone/Acoustic										
ER3 (F)	Mean	5.3	5.2	0.2	2.8	−0.5	−8.7	−2.5	−0.5	−0.8
	s.d.	4.1	3.3	4.5	4.4	2.5	2.7	4.4	2.4	1.7
ER3 (P)	Mean	10.5	10.3	7.2	9.8	4.2	−5.5	−2.7	−1.0	−0.2
	s.d.	6.1	3.0	6.0	5.6	3.1	3.2	3.1	2.2	0.8
HDA200	Mean	9.7	1.3	0.0	−1.8	−1.7	−0.5	0.3	0.3	1.0
	s.d.	4.3	6.1	4.3	4.4	3.4	1.9	2.1	2.7	1.3
TDH50	Mean	18.2	13.0	3.2	5.0	1.5	−2.2	1.5	3.0	2.5
	s.d.	8.2	6.1	8.3	10.4	6.6	8.0	5.0	5.9	6.9
Earphone/Psychoacoustic										
ER3 (F)	Mean	3.3	4.2	2.5	−0.8		−1.7		0.0	
	s.d.	6.1	7.4	5.2	5.8		4.1		0.0	
HDA200	Mean	5.0	1.7	0.8	−0.8		0.8		0.0	
	s.d.	4.5	6.8	8.0	7.4		3.8		3.2	
TDH50	Mean	16.0	15.0	8.0	3.0		−1.0		1.0	
	s.d.	4.2	3.5	2.7	4.5		2.2		2.2	

Margolis & Moore 2011

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Accurate air conduction thresholds

- Properly placed supra-aural earphones
  - Can affect 4KHz, 6KHz, 8KHz (find reference)
  - Collapsing ear canal
- Condition of earphone cushions
  - Cracked and/or hardened cushions attenuate less ambient noise in LF
  - Should be replaced annually
- Properly fit insert earphones
  - Good acoustic seal (low frequencies can escape – venting)
  - Deep insertion (without discomfort)
    - Reduces occlusion effect
- Circumaural headphones
  - Easier to place
  - Little or no occlusion effect

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MX41/AR
Needs Replaced

New MX41/AR
Cushions

Model 51

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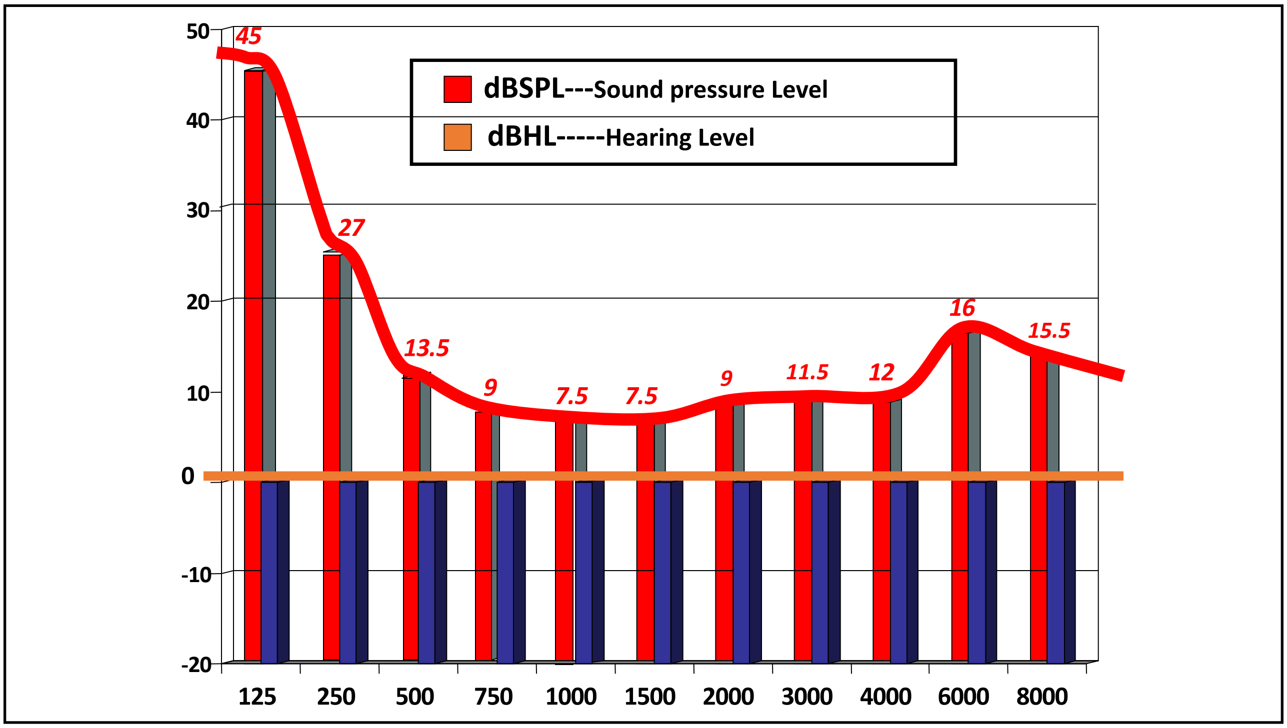
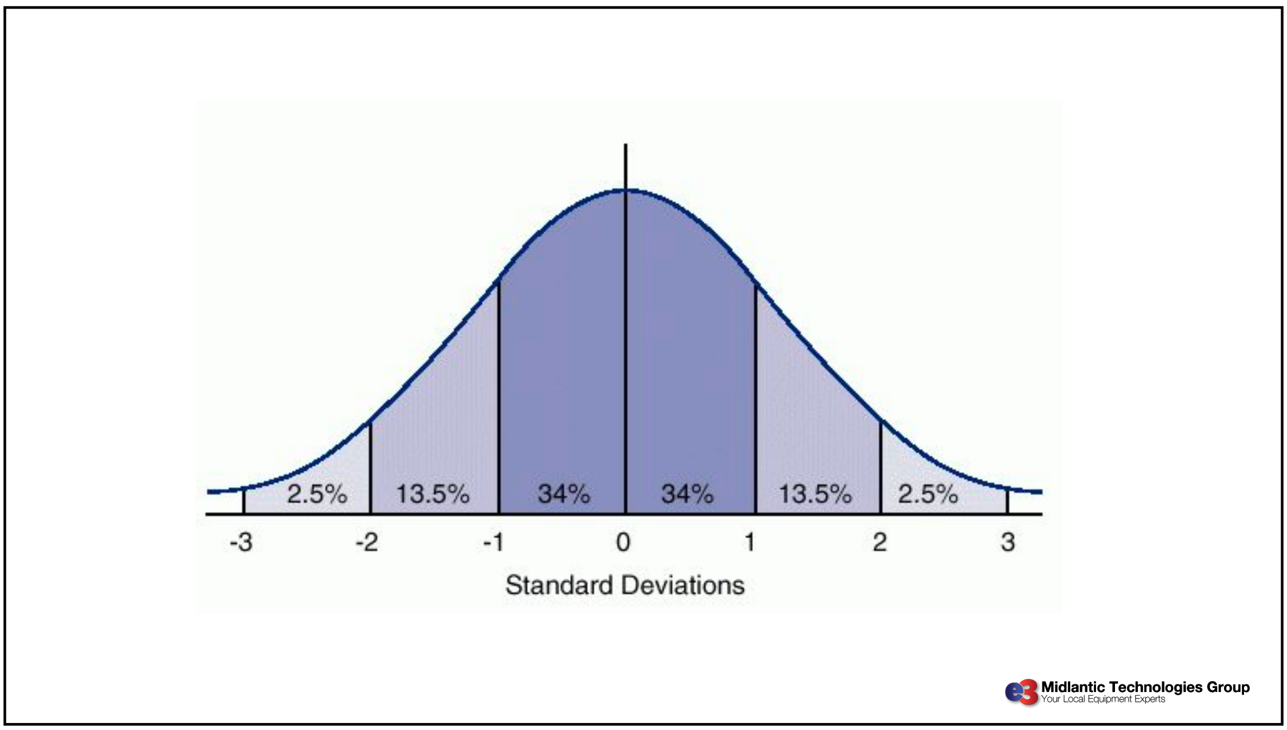


dBSPL---Sound pressure Level
dBHL-----Hearing Level
50
40
30
20
10
0
-10
-20
45
27
13.5
9
7.5
7.5
9
11.5
12
16
15.5
125
250
500
750
1000
1500
2000
3000
4000
6000
8000

31



2.5%
13.5%
34%
34%
13.5%
2.5%
-3
-2
-1
0
1
2
3
Standard Deviations
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Reference threshold levels and a normal distribution

- BC thresholds are more variable than AC thresholds
- ABG is a normally distributed variable based on the variability between two threshold measurements that form the difference (AC & BC)
- Assuming a 5dB SD of the ABG, a 0dB ABG would only occur about 38% of the time (Studebaker 1967)
- Does the sample population used to generate reference threshold levels represent the patient population being tested?
  - If so, you would expect that same variability in the outcomes

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TABLE 1. Expected distribution of the air-conduction, bone-conduction threshold relationship in subjects with normal middle ear function assuming a standard deviation of the distribution of differences of 5 dB.

Measured AC-BC Relationship	*Actual AC-BC Relationship*	*Percentage in Interval*
−20 or more	−20 or greater	0.02
−15	−17.5 to −12.5	0.60
−10	−12.5 to −7.5	6.06
−5	−7.5 to −2.5	24.17
0	−2.5 to +2.5	38.29
+5	+2.5 to +7.5	24.17
+10	+7.5 to +12.5	6.06
+15	+12.5 to +17.5	0.60
+20 or more	+20 or greater	0.02

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Other variables affecting PT air & bone thresholds

Affect air & bone similarly

- Sensori-neural sensitivity
- Attention
- Fatigue
- Experience

May affect air & bone differently

- Efficiency of the middle ear
- Length and shape of EAM
- Thickness of skin and subcutaneous tissue
- Head shape and size

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Tester Bias and the ABG

- ***Confirmation bias***—evaluating evidence that supports one's preconceptions differently from evidence that challenges these convictions (Kaptchuk 2003)
- ***Diagnostic suspicion bias*** - occurs when knowledge of the subject's past history influences the outcome of a diagnostic process (Margolis et al 2016)
- ***Previous opinion bias*** **-** occurs when a previous diagnostic procedure influences the administration and result of a subsequent measurement (Margolis et al 2016)
- ***"Interpretation is never completely independent of a scientist's beliefs, preconceptions, or theoretical commitments" (Kaptchuk 2003)***
- Expectation of outcome influences judgement and recording of results

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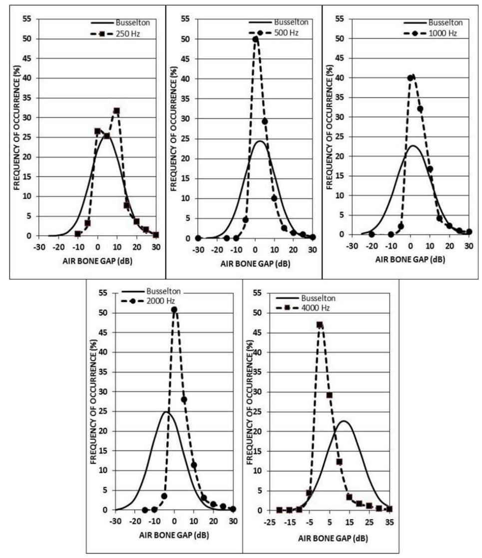
Tester Bias and the ABG

Margolis et al (2016) - Distribution Characteristics of Air-Bone Gaps – Evidence of Bias in Manual Audiometry

- Results obtained via manual testing compared to automated testing
- Manual audiometry databases show significant levels of positive skew, indicating an under-representation of negative ABGs
  - Translation – audiologists were not reporting bone conduction thresholds as measured in the presence of a negative ABG
- How can tester bias be documented?
  - Compare thresholds measured manually to those measured using an automated approach



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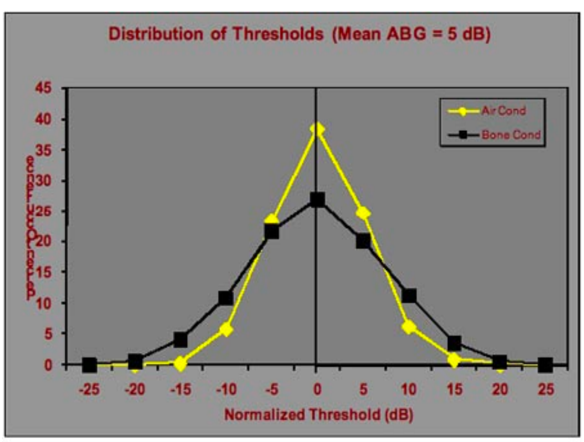
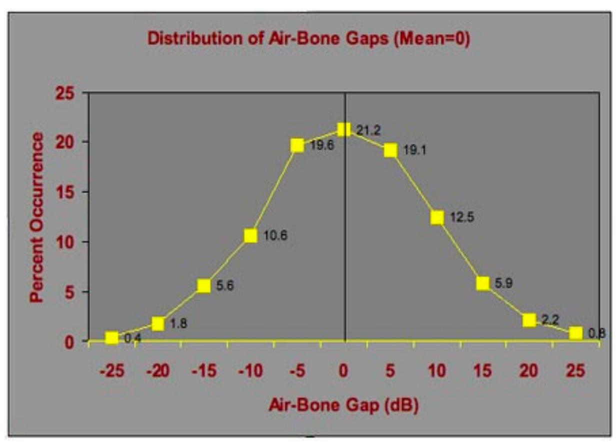
Tester Bias and the ABG



Distributions of air and bone conduction thresholds that would occur on repeated testing of an individual patient with normal hearing or sensorineural hearing loss with an air-bone gap of 0 dB



Distribution of air-bone gaps based on the air and bone conduction threshold distributions in Figure 2. The figure shows the variation in air-bone gaps that are expected on repeated testing of an individual patient when the average air-bone gap is zero

Margolis 2008

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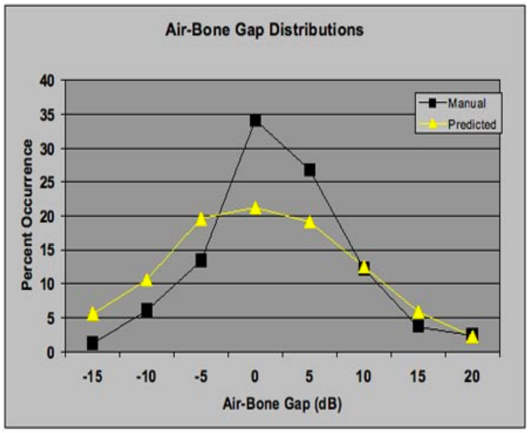
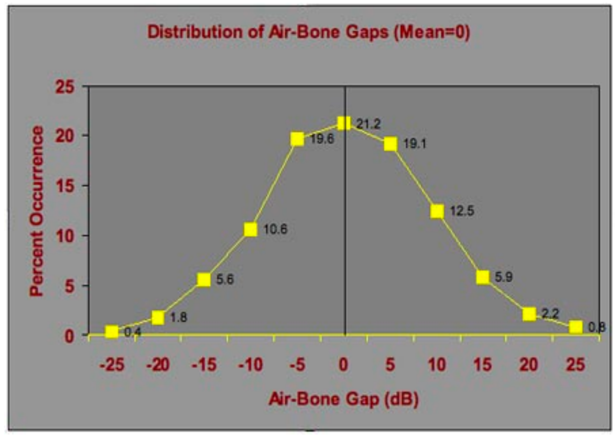
Tester Bias and the ABG



Distribution of air-bone gaps for a set of audiograms on patients with sensorineural hearing loss. Air-bone gaps from manual audiometry (squares) by an expert audiologist and the predicted distribution from Figure 3 (triangles) are shown. There are more air-bone gaps of 0 and 5 dB and fewer of -5, -10, and -15 in the manually-obtained audiograms compared to the predicted distribution.



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Margolis 2008

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Tester Bias and the ABG

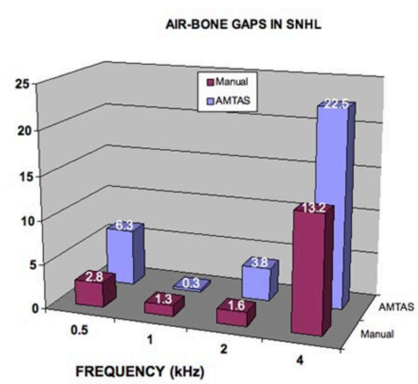

Figure 9. Average air-bone gaps for 11 patients with sensorineural hearing loss with manual audiometry and an unbiased automated method (AMTAS). The aberrant air-bone gaps at 4 kHz are larger with the automated procedure.

Margolis 2008

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Tester Bias and the ABG

[Margolis et al (2016)]

The findings…

1. ABGs are normally distributed (confirms Studebaker findings)
2. The ABG SD for manual testing was 6dB; for automated testing it was 8.1dB (includes all frequencies)
   a. Smaller SDs for manual testing reveal effect of tester bias on variance of results
3. Fewer negative ABGs recorded during manual testing
4. Tester bias may cause misinterpretation of audiometric results
   a. ABGs in cases of vestibular pathology (LVA, SCD)
5. The more knowledge the clinician has about the patient, the greater the potential bias
   a. Recording of BCT influenced by having already measured ACT

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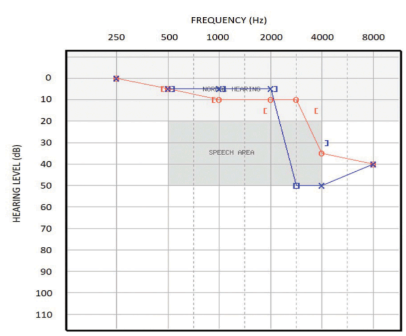
The dreaded 4KHz ABG

- A fairly common occurrence in clinical testing
- Different theories advanced
  - Collapsed canals
  - Acoustic radiation
  - Accuracy of the calibration value at 4KHz
  - Audiometer out of calibration at 4KHz
  - Could it really be conductive in nature
    - Change in ME transmission that is age-related
  - Size of ABG may be related to degree of SNHL
    - ABG increases as AC threshold increases in ears with normal ME function



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The dreaded 4KHz ABG

Collapsed ca

- Occurs n the press from SA head on use a mo arrow canal to co pse
  - M e common der pa nts
  - D not occur if CA adphones use
- Collapsed n about 4% of patients (Lynn 1969)

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The dreaded 4KHz ABG

Acoustic radiatio

- A popula lanation… T
- Numer s s es reveale ttle (1-4dB) or no i prove t in BC t sholds
  - Co red BC t olds me red with the ear occluded a clude
  - B71 d B71A bone t

ALTHOUG

- SPL readings o tic energy from a BC suggest otherwise…take a look

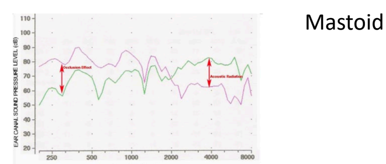

Figure 7. Ear canal sound pressure level measurements for a bone conducted stimulus delivered to the mastoid with the ear canal open (green) and plugged (pink). The low-frequency occlusion effect is an increase in sound pressure resulting from occluding the ear canal. The acoustic radiation effect is evident from the higher ear canal sound pressure when the ear is open compared to the plugged condition that blocks the sound reaching the ear canal by air conduction.

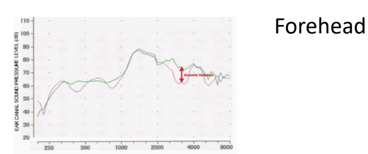

Figure 8. Ear canal sound pressure level measurements for a bone conducted stimulus delivered to the forehead with the ear canal open (green) and covered with a circumaural earphone (pink). The low frequency occlusion effect is minimal (compare to Figure 7). The acoustic radiation effect is much smaller when the bone vibrator is on the forehead.

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The dreaded 4KHz ABG

Calibration RETFL at 4KHz

- Accuracy is questioned based upon studies conducted in the 1950's and 1960's
  - Force levels measured based on BC thresholds obtained
  - But not on the B&K 4930
- Current RETFLs based on three studies
  - Force levels measured on B&K 4930
- Could the questionable RETFL at 4KHz be related to the calibration device?

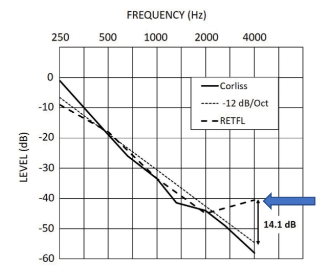

FIGURE 2. The solid line illustrates bone-conduction threshold as a function of frequency (Corliss et al, 1959). The dotted line has a slope of -12 dB/octave. The dashed line shows the RETFLs from the audiometer standards.

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What to do?

- Nothing – but understand that this may be the reason an unexplained ABG occurs at 4KHz in patients with SNHL and a normal middle ear
  - Educate physicians
- Add a correction factor
- Change the calibration RETFL
  - Ask your calibration company to reduce the output of the bone vibrator
  - Be prepared to justify this adjustment with peer-reviewed articles
  - This may violate federal and state regulations
- Don't test bone conduction at 4KHz

Margolis et al (2019)

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The dreaded 4KHz ABG

- Could it be a true conductive or mixed loss?
  - Unlikely if it's just at 4KHz; but…
  - But changes in ME transmission properties occur with age
    - So could this change be related to the air conduction threshold?
    - Nixon and Glorig (1962) found just that; others studies have not supported their finding
- Degree of SNHL affects the ABG at 4KHz
  - As SNHL increases so does the size of ABG
  - Range is from 10dB to 22.1dB (normal to severe HL)

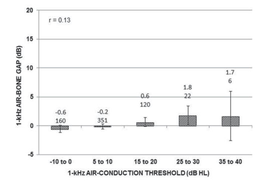

Figure 1. Average 1-kHz air-bone gaps for participant groups stratified by the 1-kHz air-conduction threshold. Data from Eikelboom & Swanepoel, unpublished. Data labels are average air-bone gap and sample size. Vertical lines are 5% confidence intervals.

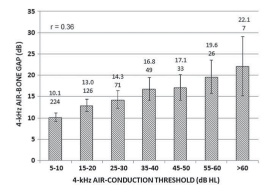

Figure 2. Average 4-kHz air-bone gaps for participant groups stratified by the 4-kHz air-conduction threshold. Data from Eikelboom & Swanepoel, unpublished. Data labels are average air-bone gap and sample size. Vertical lines are 5% confidence intervals.

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Mastoid or Forehead

- Over 90% of audiologists use mastoid placement
  - Need more force applied at the forehead to reach threshold
  - Hearing threshold is less (better) with mastoid placement
  - Higher maximum output attained
    - B81 bone vibrator – increases overall maximum output in the low to mid frequencies
  - Closer to the cochlea being tested
  - It's how most audiologists are trained

But we also know the potential problems associates with mastoid placement…

- Smaller surface area on which to place bone vibrator
- Shifts in the position during testing will cause larger changes in BC threshold
- Middle ear contributes to BC thresholds

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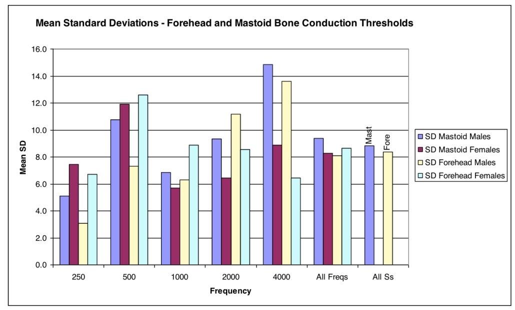
Advantages of forehead placement

- Larger surface area – slight shift in location has little effect on threshold
- Better test-retest reliability
- Reduced intra-subject variability
- Less contribution from the ME
- Use of circumaural headphones eliminates
  - The occlusion effect
  - The need to reposition the bone vibrator when switching ears, and
  - Saves time



Standard deviations for each test frequency for bone conduction thresholds averaged for the left and right ears. The right most bars show SDs averaged across frequencies and subjects for the two locations

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Questions?

50

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