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ELECTROACOUSTIC CALIBRATION FOR SOUND FIELD WARBLE TONE THRESHOLDS

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Walker, Dillon, and Byrne (1984) suggested reference equivalent threshold sound pressure levels (RETSPLs) for warble tones with specific modulation parameter values audited from a test position at the critical distance in a semireverberant sound field. This study evaluated these RETSPLs in two typical audiometric rooms and with typically encountered FM tones. Thresholds were measured under earphones and in two sound fields for 6–11 normal hearers at six test frequencies. Results indicated that there was a small but statistically significant difference between earphone and sound field thresholds in 4 of 24 comparisons. However, in both sound fields, 99% of the sound field thresholds were within 10 dB of the earphone thresholds. It is concluded that these RETSPLs are appropriate for electroacoustic calibration of sound field warble tones similar to those used in this study.

Although sound field threshold testing using frequency-specific stimuli plays an important role in pediatric hearing assessment and in many hearing aid selection procedures, no standard reference equivalent threshold sound pressure levels (RETSPLs) have been established for sound field testing. ISO Recommendation R266 (1961) gives normal hearing threshold values for pure tones under free field listening conditions but these have not been widely recommended for audiological calibration purposes because typical sound field threshold testing employs neither pure tones nor free field listening.

Sound field thresholds typically are measured in audiometric test rooms that have semireverberant rather than anechoic characteristics. Because of the occurrence of standing waves in this type of environment, reliable calibration of pure-tone stimuli is particularly difficult to achieve. One approach to this problem involves the use of frequency-modulated (warble) tones for sound field threshold tests. Because these stimuli encompass a greater bandwidth than pure tones, their overall level at the listener's ear is less influenced by standing waves in the sound field.

Because there are no established RETSPLs for warble tones in a semireverberant field, audiological facilities wishing to express sound field thresholds in terms of hearing loss are forced to resort to biological calibration methods. Typically, earphone and sound field thresholds are measured on a group of normal hearing persons, and sound field calibration is established by determining correction values that result in equivalent hearing sensitivity for earphone and sound field test conditions. This procedure has several serious drawbacks: (a) Ambient noise levels in the test environment are frequently high enough to mask sound field thresholds for very sensitive normal hearers, and most test facilities are not equipped to assess this issue; (b) audiometer attenuators are often nonlinear at low levels, which leads to inaccurate threshold measurement for normal hearing persons; and (c) even when the above problems are managed, the time-intensive nature of the procedure usually results in infrequent repetitions of the calibration check and reliance on small data sets to derive calibration values. These considerations indicate that there is a significant need for standard RETSPLs for warble tone sound field testing.

One impediment to the establishment of such a standard is the considerable variability in the parameters of FM tones provided with audiometers. Modulation bandwidth, modulation waveform, and modulation rate differ considerably across instruments, and these factors are often not described in the manufacturer's documentation. Several investigators have reported that the values of these parameters have significant acoustic and/or psychoacoustic consequences (Barry & Resnick, 1978; Dillon & Walker, 1982). The other major problem facing individuals attempting to establish standard sound field RETSPLs is the often inscrutable effects of different room shapes, sizes, and contents on the distribution of acoustic energy at the test position. In spite of these problems, notable contributions to the standardization of warble tone sound field threshold testing have been made by Morgan, Dirks, and Bower (1979) and by Walker, Dillon, and Byrne (1984).

Morgan et al. (1979) established monaural RETSPLs for FM tones delivered from a 45° azimuth. The FM characteristics were: bandwidth equals +5% (i.e., 5% upward from nominal frequency), modulation rate equals 6 per second, and modulation waveform not specified. These RETSPLs were used to establish sound field calibration in an audiometric test room. Mean sound field thresholds measured at six frequencies were compared to corresponding earphone thresholds for 61 hearing-impaired subjects. Typical mean differences were less than 2 dB. Morgan et al. concluded that accurate electroacoustic calibration of warble tones in the sound field was possible, but they cautioned against uncritical use of their suggested reference levels for sound fields having characteristics different from the one in which their data were collected or for FM tones having other parameter values.

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Walker et al. (1984) presented a comprehensive set of recommendations for appropriate parameter values of FM tones used for sound field threshold testing. These values, determined on the basis of a series of investigations, included modulation bandwidths decreasing from about 30% at 250 Hz to 8% at 4000 Hz, modulation rate of 20 per second, and sinusoidal or triangular modulation waveforms. For FM tones satisfying these requirements and for test positions located at the critical distance for that sound field (i.e., the location where direct sound level equals reverberant sound level), they suggested RETSPLs for 0° and 90° azimuth signals.

Table 1 gives monaural RETSPLs for 0° azimuth sound field signals that can be derived from ISO R266 (1961) (to estimate monaural thresholds, 3 dB have been added to the suggested binaural threshold values), Morgan et al. (1979), and Walker et al. (1984). Considering the different stimuli, acoustic environments, and test procedures employed in the derivation of each set of values, their similarity is remarkable. This observation provided the impetus for an investigation that explored the application in two audiometric test environments of the RETSPLs suggested by Walker et al. Although the two environments were quite typical of audiology clinics in the U.S.A., neither conformed to the recommendations of Walker et al. in terms of the FM tone parameter values or the location of the test position.

The research questions were:

1. If the RETSPLs suggested by Walker et al. (1984) are used for calibration of sound field FM tones, is there a significant difference for normal hearers between hearing threshold levels measured in the sound field and corresponding threshold levels for pure tones measured under earphones?
2. Is the agreement between sound field and earphone thresholds different for (a) FM tones having rectangular modulation at 3.5 Hz presented in one audiometric test room (Sound Field A) and audited from a position different from the critical distance or (b) FM tones having triangular modulation at 6.2 Hz presented in a different audiometric test room (Sound Field B) and audited from a position different from the critical distance?

TABLE 1. Monaural reference equivalent threshold sound pressure levels (RETSPLs) derived from three sources for signals presented in a field from a 0° azimuth.

Frequency	*R226*[a]	*M, D, & B*[b]	*W, D, & B*[c]
250	14.5	15.0	16.0
500	9.0	11.5	9.5
1000	7.0	8.0	5.5
2000	4.0	2.5	2.5
3000	0.0	–	0.5
4000	−1.0	2.5	1.5

[a]ISO Recommendation R266 (1961), Figure 1. [b]Morgan, Dirks, and Bower (1979), Table 2. [c]Walker, Dillon, and Byrne (1984), Table 3.

METHOD

Sound Fields

Two double-walled, sound-treated, Industrial Acoustics Corporation audiometric test rooms comprised the sound field environments. The dimensions (L × W × H) of Sound Field A (SFA) were 2.44 m × 2.13 m × 2.18 m (96 in. × 84 in. × 86 in.). The (coaxial) loudspeaker was mounted in one corner with the cone center at a height of 1.14 m (45 in.). The test position was located at a height of 1.14 m (45 in.) in the geographic center of the room, 1.27 m (50 in.) from the front of the loudspeaker. The dimensions of Sound Field B (SFB) were 2.74 m × 2.13 m × 1.98 m (108 in. × 84 in. × 78 in.). The (coaxial) loudspeaker was mounted in the middle of the long wall with the cone center at a height of 1.14 m (45 in.). The test position was located 1.14 m (45 in.) from the floor and 1.04 m (41 in.) from the front of the loudspeaker and on the loudspeaker axis. Each room contained one glass window and was bare of furniture except for the listener's chair. Ambient noise levels in each environment were measured and compared to ANSI S3.1-1977 to determine the lowest sound field thresholds that could be measured at each test frequency; these ranged from −9 to 2 dB HL.

Test Stimuli

In each sound field, thresholds were measured at six nominal frequencies (250, 500, 1000, 2000, 3000, and 4000 Hz) for warble tones presented from a 0° azimuth. In SFA, the FM tones were produced by a Saico SC8 audiometer. The tone parameters were: mean modulation bandwidth equals −4.7% (i.e., downward from the nominal frequency); modulation rate equals 3.5 per second; and modulation waveform, rectangular. This audiometer had been modified to produce a signal at 2500 Hz instead of at 3000 Hz. For normal hearers, this could result in an improvement in sound field thresholds of 1–2 dB; this was kept in mind during data interpretation. In SFB, the FM tones were produced by a Grason-Stadler GSI10 audiometer. The tone parameters were: mean modulation bandwidth equals +/−4.6% (i.e., both upward and downward from the nominal frequency, resulting in a mean total bandwidth of 9.2%); modulation rate equals 6.2 per second; and modulation waveform, triangular. Figure 1 illustrates the differences in these two types of warble tone signals. The figure shows the long-term RMS spectra of FM tones at a nominal 4000-Hz frequency measured at the output of each audiometer. These data were obtained using a Hewlett Packard Model 3561A spectrum analyzer set to a 38-Hz analysis bandwidth.

Earphone thresholds were measured for pure tones produced by the Grason-Stadler GSI10 audiometer at 250, 500, 1000, 2000, 3000, and 4000 Hz. The transducer was a Telephonics TDH-50 earphone encased in a Telephonics P/N 51 cushion.

Subjects

Fourteen normal hearing young adults participated in the study. Both ears were tested.

Calibration

Daily calibration checks were performed on both sound fields and the TDH-50 earphone using a Larson.Davis Model 800B precision sound level meter. For each condition, stimuli were calibrated (to the nearest 1 dB) in hearing threshold levels (HL). The prevailing audiometer standard (ANSI S3.6–1969) does not encompass reference equivalent threshold levels for TDH-50 earphones. Therefore, RETSPLs from the proposed revision to this standard were used to calibrate the earphone. The RETSPLs proposed by Walker et al. (1984), included in our Table 1, were used for calibration of FM tones in both sound fields. As recommended by these authors, the warble tone measurements were made by observing peak deflections with the sound level meter adjusted to "fast" response.

Attenuator linearity was measured for both audiometers, and both were found to meet the ANSI S3.6-1969 standard for linearity from −10 to 70 dB HL.

Procedures

Thresholds were obtained using the standard ascending test procedure except that a 2-dB ascending step size was used instead of the usual 5-dB step ("Guidelines," 1978). During earphone testing, the subject was seated in SFB and the nontest ear was covered with a nonoperational earphone/cushion assembly. During sound field testing, the subject (seated) was carefully located at the test point in the room and instructed to remain still and focus visually on a marked point on the front of the loudspeaker. No head restraint or height adjustment was used. The nontest ear was plugged and circumaurally muffed (Amplivox audiocup muff).

Presentation of the three conditions—earphone, SFA, and SFB—was counterbalanced across subjects. The six test frequencies were always presented in ascending order from 250 to 4000 Hz.

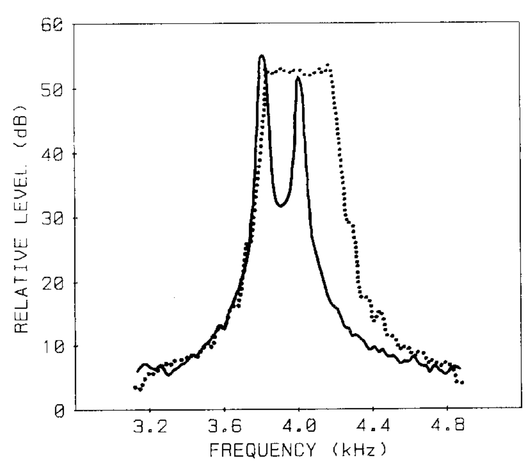

FIGURE 1. Long-term RMS spectra of the two types of warble tones. The nominal frequency of both stimuli was 4000 Hz. The solid line illustrates the spectrum of the FM stimulus produced by the Saico SC8 audiometer. The dotted line illustrates the spectrum of the FM stimulus produced by the Grason-Stadler GSI10 audiometer.

RESULTS

The data were expressed in dB HL for the earphone (pure tone) and both sound field (FM tone) conditions. For each frequency/ear combination, data for a given subject were accepted only if thresholds for all three test conditions were higher than the limits imposed by ambient noise and attenuator nonlinearity. As a result, the number of retained data values varied with frequency and ear (left or right).

Twelve separate one-way analyses of variance (repeated measures) were performed: one for each frequency/ear combination. Left and right ears were analyzed separately because it seemed possible that asymmetric sound field acoustics might have significant effects on thresholds for one ear but not the other. When significant differences were detected, a least significant difference multiple comparison test was performed. The comparisons of interest for each frequency/ear combination were between the earphone threshold condition and each sound field threshold condition. Because of the large number of separate tests performed, a level of significance of .01 was selected to reduce the likelihood of a Type I error in determining significant differences.

The results are summarized in Table 2. This table gives the mean thresholds measured for each frequency/ear combination in the earphone and both sound field conditions. Of the 24 earphone-sound field threshold comparisons, 4 yielded significantly different thresholds: at 250 Hz, thresholds measured in SFB were higher (poorer) than the corresponding earphone measures for both ears;

TABLE 2. Mean thresholds (dB HL) for earphone and both sound field conditions. Standard deviations (dB) are given in parentheses. N = number of ears.

	Right ear				*Left ear*			
Frequency	*TDH-50*	*SFA*	*SFB*	*N*	*TDH-50*	*SFA*	*SFB*	*N*
250	2.1	2.3	6.5[a]	8	1.6	3.0	5.4[a]	9
	(5.6)	(4.6)	(4.6)		(5.3)	(4.8)	(5.3)	
500	6.8	1.3[a]	6.0	6	2.7	1.9	5.3	9
	(2.5)	(1.2)	(4.6)		(5.0)	(5.8)	(6.2)	
1000	2.4	1.3	3.6	11	1.4	4.1	3.3	9
	(4.3)	(5.7)	(4.9)		(6.9)	(6.3)	(7.3)	
2000	1.9	4.4	6.1	8	4.8	4.3	5.1	8
	(5.6)	(2.6)	(3.0)		(6.9)	(4.8)	(6.6)	
3000	1.5	0.5	8.4[a]	8	4.3	2.1	5.6	8
	(7.4)	(5.8)	(6.5)		(7.4)	(3.9)	(6.6)	
4000	7.4	3.4	6.6	7	7.9	3.0	5.4	8
	(7.8)	(6.3)	(6.3)		(7.7)	(4.8)	(7.4)	

[a]Significantly different from earphone threshold, $p < .01$.

at 500 Hz, thresholds measured for SFA, right ear, were lower than the corresponding earphone thresholds, but this was not true for the left ear data; and at 3000 Hz, thresholds measured for SFB, right ear, were higher than the corresponding earphone thresholds, but this was not true for the left ear data. There were no instances in which the thresholds measured in both sound fields were significantly different from the earphone data.

To evaluate the correspondence between earphone and sound field thresholds on an individual rather than a group basis, differences were derived between sound field and corresponding earphone thresholds for each subject in all conditions. Data from both ears and all frequencies were combined. In SFA, the mean sound field-earphone threshold difference was −0.9 dB, and the standard deviation of the distribution was 5.3 dB. In SFB, the mean difference was 1.9 dB, and the standard deviation of the distribution was 5.1 dB.

Because clinical threshold tests typically use a 5-dB ascending step rather than the 2-dB step used in this study, the data were recoded to estimate the sound field-earphone threshold differences that would have been observed with the customary clinical procedures. Figure 2 shows the distribution of the sound field-earphone threshold differences derived in each sound field condition. Data from both ears and all frequencies are combined in this figure. In SFA, 78% of the sound field thresholds were within 5 dB of the corresponding earphone thresholds, and 99% were within 10 dB. In SFB, 85% of the sound field thresholds were within 5 dB of the corresponding earphone thresholds, and 99% were within 10 dB.

Table 2 shows that the mean thresholds measured in SFA were lower than the corresponding mean thresholds in SFB for all conditions except 1000 Hz, left ear. This suggests a small but systematic difference in detectability between the two types of FM tones used. If the detectability of the two types of sound field FM tones were essentially equal, we would expect that, overall, thresholds measured in the two sound fields would be equivalent. Although it is certainly true that the differing acoustical effects in the two sound fields may interact with differences between the FM tones, there is no reason to expect sound field effects to influence thresholds in the same way at all frequencies. To compare the detectability of the two FM tones, a sign test was performed on the right ear threshold data for the two sound field conditions. All tested frequencies were combined. Of the 51 pairs of thresholds considered in this test, the threshold in SFB was higher than that in SFA in 42 pairs. The probability of this occurring by chance is less than .001. A second sign test was performed on the left ear data with identical results. This outcome suggests that the FM tones produced by the Saico SC8 audiometer were more detectable than those produced by the Grason-Stadler GSI10 instrument. Hence, when both were calibrated using the same RETSPL values, the FM tones in SFA yielded lower thresholds than the FM tones in SFB.

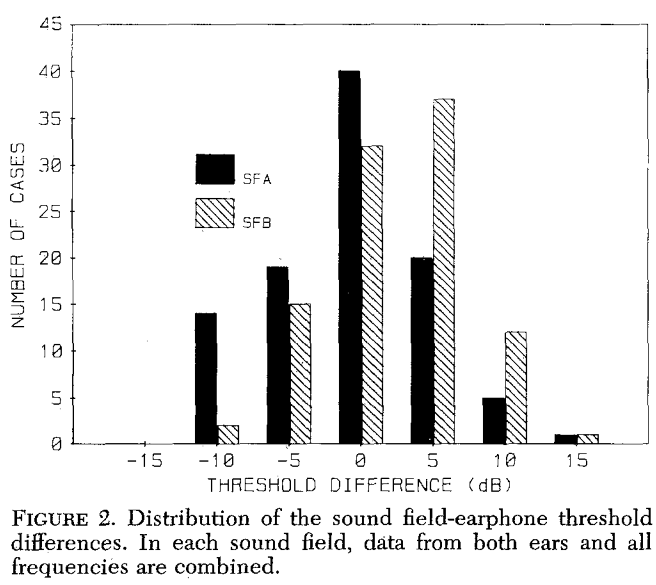

FIGURE 2. Distribution of the sound field-earphone threshold differences. In each sound field, data from both ears and all frequencies are combined.

DISCUSSION

The results suggest that the procedure used in this study for electroacoustic calibration of sound field warble tones is likely to result in a small proportion of errors in sound field threshold determinations. Specifically, mean sound field thresholds were significantly different from the corresponding mean earphone thresholds in 17% of the comparisons. There are several possible reasons for such an outcome: (a) The RETSPLs suggested by Walker et al. (1984) might be inappropriate for sound fields of this type; (b) these RETSPLs might be inappropriate for warble tones with the bandwidths, modulation rates, and modulation waveforms used in this investigation; or (c) the acoustic effects in audiometric test rooms may be so extreme and/or asymmetric as to render electroacoustic calibration of warble tones unfeasible.

If the RETSPLs suggested by Walker et al. were inappropriate for the sound fields found in typical audiometric test rooms, we would expect to find that mean earphone thresholds were consistently significantly different from mean sound field thresholds for both audiometric rooms. In fact, even for the 17% of comparisons that revealed statistically significant differences between sound field and earphone thresholds, the magnitudes of the differences were probably not clinically significant. The largest mean difference observed under any condition was 6.9 dB. This suggests that the RETSPLs were rather good estimates of the required values.

There was evidence that the warble tones generated by the Saico audiometer were slightly more detectable than those generated by the Grason-Stadler instrument. This result is in agreement with the report by Barry and Resnick (1978), who found that tones with lower modulation rate resulted in lower thresholds at all tested frequencies, regardless of modulation waveform (sinusoid or ramp) or bandwidth. However, the absolute magnitude of the threshold differences between the two types of FM tones (mean difference = 3 dB) was probably too small to be of practical significance in a clinical test. This outcome suggests that the

RETSPLs suggested by Walker et al. (1984) may be used with FM tones similar to the ones used in this study even though these had different modulation parameters from the tones recommended by Walker et al.

In addition, there was evidence of idiosyncratic sound field effects that resulted in unpredictable, sometimes asymmetric, threshold differences in sound field tests. For example, in SFA at 500 Hz the right ear thresholds were consistently lower than the left ear thresholds, an effect that was not observed at any other frequency. This particular test signal was so detectable that acceptable data could not be obtained for many subjects because they continued to hear the FM tone even at the lowest linear attenuator setting. The relatively high mean earphone threshold in this condition (6.8 dB) reflects the elimination of the more sensitive subjects from the data. Idiosyncratic sound field effects probably also account for the significant differences between sound field and earphone thresholds for SFB, right ear, at 3000 Hz and at 250 Hz for both ears. Morgan et al. (1979) reported similar rare, arcane sound field threshold effects.

The standard deviations of the sound field-earphone threshold differences averaged 5.2 dB. This suggests that sound field thresholds measured as in this study will deviate from the corresponding earphone thresholds by more than 10 dB about 5.5% of the time (assuming the population data to be normally distributed around a mean of 0 dB). In evaluating this outcome, it is instructive to compare these data with test-retest differences reported by Byrne and Dillon (1980) for warble tone thresholds measured 1 day apart. These investigators used 1 min of fixed-frequency Bekesy tracking for each threshold determination. They reported that the standard deviation of test-retest differences for earphone thresholds was 4.1 dB. For repeated determinations of sound field thresholds, the standard deviation of test-retest differences was 4.6 dB. These data suggest that the normal variability of thresholds would result in test-retest differences that exceed 10 dB about 2% of the time even if sound field and earphone calibration were in perfect synchrony.

When the sound field-earphone threshold differences were expressed in 5-dB increments for comparison to typical clinical procedures (Figure 2), the differences observed between them were no greater than those observed in repeated clinical tests of earphone thresholds (see, e.g., Jerger, 1962). Specifically, essentially all of the sound field thresholds were within 10 dB of the corresponding earphone thresholds.

In summary, the results indicate that electroacoustic calibration, using the RETSPLs suggested by Walker et al. (1984), of sound field warble tones similar to the ones used in this study (triangular or rectangular modulation at 3–6 Hz with 5–10% bandwidth) is likely to result in a small proportion of statistically significant discrepancies between sound field thresholds and corresponding earphone thresholds. These discrepancies are partly due to minor, probably predictable, differences in detectability of warble tones with varying modulation parameter values and partly due to unpredictable, perhaps asymmetric, acoustic effects related to the specific sound field used. On the other hand, the data also suggest that the absolute magnitude of these sound field-earphone threshold differences is not likely to be clinically significant. Viewed from this perspective, any errors possibly introduced by the use of electroacoustic calibration appear quite minor, particularly when weighed against the demands on both equipment and personnel of rigorously maintained biologic sound field calibration.

One final consideration should be mentioned. Walker and Dillon (1983) suggested that individuals with impaired temporal integration should be tested using FM tones with a modulation rate of 20 Hz because a slower rate could result in responses to individual peaks in the stimulus bandwidth. However, Morgan et al. (1979) tested 61 hearing-impaired subjects using an FM tone modulation rate of 6 Hz. Their data suggested excellent agreement for this group of subjects between earphone pure-tone thresholds and sound field FM tone thresholds measured in an audiometric test room. Further study is required to evaluate the importance of fast modulation rates for FM tones presented in audiometric test rooms. In the meantime, audiologists should use the fastest modulation rates available when performing sound field warble tone tests.

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