Analysis of Nonstandard Noise Dosimeter Microphone Positions

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This study was conducted as part of a project involving the evaluation of a new type of noise exposure monitoring paradigm. Laboratory tests were conducted to assess how "nonstandard" dosimeter microphones and microphone positions measured noise levels under different acoustical conditions (i.e., diffuse field and direct field). The data presented in this article reflect measurement differences due to microphone position and mounting/supporting structure only and are not an evaluation of any particular complete dosimeter system. To varying degrees, the results obtained with the dosimeter microphones used in this study differed from the reference results obtained in the unperturbed (subject absent) sound field with a precision (suitable for use in an ANSI Type 1 sound level meter) 1/2-inch (12.7 mm) measurement microphone. Effects of dosimeter microphone placement in a diffuse field were found to be minor for most of the test microphones/locations, while direct field microphone placement effects were found to be quite large depending on the microphone position and supporting structure, sound source location, and noise spectrum.

Keywords dosimeter, microphone, noise

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INTRODUCTION

The technique for measuring a worker's daily noise dose with a person-worn device was developed in the 1960s. Until this time most noise exposure measurements were obtained with a hand-held sound level meter, using a stopwatch to quantify the exposure duration. Microphone placement was one issue to resolve when determining the accuracy of newly developed personal noise dosimeters. An obvious disadvantage of personal noise dosimetry is that the measurement microphone may be shielded from a directional noise source by the head/body of the wearer. This "shadow" or "baffle" effect may cause a measurement inaccuracy of several decibels under certain conditions, for example, where there are few reflective surfaces.

A government report written by Muldoon(1) in 1973 described the results of an investigation to quantify the magnitudes of response variations for four microphone placements (center of the chest, left breast pocket, between the shirt-collar tabs, and on top of the left shoulder) and two microphone orientations (pointing vertically upward and pointing horizontally forward at the sound source) on an anthropometric dummy in a free field. Muldoon's general conclusions stated that for azimuths where the body is not acting like a barrier between the sound source and the microphone, there is an increase in the lower octave bands and a decrease in the higher bands. All octave bands showed a decrease when the head or body acts as a barrier, with the greatest reduction occurring at 4000 Hz (which was the highest octave band measured). Muldoon went on to suggest that locating the dosimeter microphone on top of the shoulder (oriented parallel to the body) would yield data most comparable with that obtained with a sound level meter.

The U.S. Mine Safety and Health Administration (MSHA) was actively involved in the early use of personal noise dosimeters and in 1978 issued revised health regulations (30 CFR Parts 70 and 71) to allow the use of dosimeters in underground and surface coal mines.(2) Based on previous research and internal reports, the revised regulation stated that noise exposure measurements shall be made with the microphone located at the top of the shoulder, midway between the neck and the end of the shoulder with the microphone pointing in a vertical upward direction. This description was supplemented with a line drawing illustrating the proper microphone placement on a miner.

The two most recent research studies involving dosimeter microphone placement corroborated the selection of the MSHA top-of-shoulder position.(3,4) Part of the work reported in 1996 was based on microphone placement data collected 14 years earlier by MSHA.(5) The 1978 MSHA regulation was based on research with noise dosimeters having 1-inch (25 mm) microphones, and essentially, the same work was replicated by MSHA in 1982 using newly available 1/2-inch (12.7 mm) microphones. The original shoulder-mounted microphone placement data were collected in 45° increments, and similar data were collected at 10° azimuthal angles several years later.(6) In general, better resolution was observed with the smaller angular step size, while differences between the ½-inch and 1-inch microphone diameters did not appear to be significant. MSHA's 1995 study was a field comparison of sound level meters and noise dosimeters with shoulder-mounted microphones.(3) They determined that there was no practical difference between levels measured with sound level meters and dosimeters as long as instruments meeting ANSI S1.4 Type 2 tolerances were used.

The Occupational Safety and Health Administration (OSHA) Occupational Noise Exposure Standard and Hearing Conservation Amendment (29 CFR 1910.95) does not specify a mandatory microphone location.(7) Industrial hygiene professionals have generally adopted the MSHA top-of-shoulder position, and its use has been recommended by hearing conservation experts for more than 20 years.(8−11) A common caveat regarding the top-of-shoulder position is that the microphone should be placed on the side anticipated to receive the most noise exposure. The American National Standard Measurement of Occupational Noise Exposure (ANSI S12.19-1996, R2001) also prescribes the top-of-shoulder location (or as near as is feasible) and indicates that when an employee is consistently exposed to noise from one side, that shoulder should be chosen to wear the microphone.(12)

The current MSHA Health Standard for Occupational Noise Exposure was published on September 13, 1999 (30 CFR Parts 56, 57, 62, 70, and 71), and enforcement of the new rule began in October 2000.(13) This rule closely resembles the 1983 OSHA regulation and replaced the different standards for occupational noise exposure in coal mines and in metal/nonmetal mines with a single, new standard applicable to all mines. Section 62.110 in the 1999 MSHA regulation states that mine operators must establish a system of monitoring to assess and evaluate miners' noise exposures; however, the new rule is flexible to the extent that it does not prescribe precisely how the mine operator must accomplish these goals. As such, the exact monitoring methodology is not specified, and innovation and improvements in technology would be considered.

A start-up company (doseBusters USA, State College, Pa.) developed a monitoring protocol that purportedly solves many of the longstanding noise monitoring and hearing protection problems encountered in typical hearing conservation programs.(14,15) Their methodology/concept includes a patented device referred to as an Exposure Smart Protector (ESP). The ESP device consists of traditional hearing protection (i.e., earplugs or earmuffs) integrated with a personal noise dosimeter. The dosimeter's microphone is positioned to measure sound levels on the "protected" side of the hearing protector. With this type of arrangement, the sound level reaching the microphone at any given time will depend on exactly how the device is being worn. A user has the option of either primary (ears protected) or secondary (ears unprotected) wearing positions for the ESP. The measurement methodology is based on the concept of using both protected and unprotected noise exposures to define a miner's daily noise dose; therefore, the ESP is designed to measure and document a worker's actual at-the-ear daily noise exposure.

The ESP manufacturer approached MSHA and requested that the use of the ESP be permitted under the current noise regulation. While MSHA wants to promote practices to prevent noise-induced hearing loss, it recognizes that ESP takes a different approach to determining a miner's noise dose. Accordingly, MSHA requested that NIOSH conduct a scientific study to address the relevant research questions. The study described herein used human subjects to examine simultaneously eight microphone positions: the "standard" left/right top-of-shoulder location and three left/right pairs of "nonstandard" positions as defined by the ESP manufacturer. Results of the second part of this project, which was an evaluation of the same microphones to accurately measure the "protected" noise exposure (i.e., as measured in the ear canal) for the same human subjects, will be published separately.

METHODS

Subjects

Subjects (11 male, 2 female; age range 30–59) were recruited from employees within the NIOSH Pittsburgh campus. The test protocol was reviewed and approved by the NIOSH Human Subjects Review Board. Participants were provided with the required assurances of confidentiality, and a standard Informed Consent form was signed prior to conducting any testing. The subjects were outfitted with typical miners' coveralls and a hard hat.

Acoustical Test Environments

A room designed for measuring the real-ear attenuation of hearing protectors was used for diffuse sound field testing. The walls and ceiling are lined with an acoustically reflective surface laminated to 3/4-inch (19 mm) high-density particle board. This room meets the requirements for sound field uniformity, directionality, reverberation time, and ambient noise levels as specified in ANSI S12.6-1997 (R2002).(16) The center-of-head location (i.e., midpoint of an imaginary line drawn through the subject's ear canals) was the geometric center of the enclosure and was defined as the reference position for measurements of the undisturbed sound field (with no experimenter or subject present); all subsequent testing was referred to measurements at this point.

A small anechoic chamber was used for direct field testing. The construction of this facility allows for testing down to approximately 100 Hz, with a usable area between wedge tips of 8.5 ft (2.6 m) long by 4.3 ft (1.3 m) wide, and a height of 7.5 ft (2.3 m) from the suspended floor to the overhead wedges. The subject was located in the far-field of the noise source, which was defined as a distance of at least one-quarter wavelength of the center frequency of the lowest frequency band of interest. With the subject centered along the width of the room, there was a distance of 1.8 ft (0.55 m) from the test subject's ear to the closest wedge tips. Therefore, the lowest frequency that can be accurately measured with a subject present would have a wavelength equal to $4 \times 1.8 = 7.2$ ft ($4 \times 0.55 = 2.2$ m), which corresponds to a frequency of 157 Hz.

Test Microphones

A $^1\!/_2$-inch measurement microphone (Type 4189; Bruel & Kjaer, Naerum, Denmark) was used as the reference microphone for the center-of-head measurements. This microphone is classified for use with a Precision or Type 1 measurement system according to the American National Standard Specification for Sound Level Meters (ANSI S1.4-1983, R2001).(17) The microphone was connected to a Bruel & Kjaer ZC 0026 Input Stage and suspended via the microphone cable from the ceiling of the test chamber, such that the microphone was oriented vertically with the diaphragm pointing downward. Another identical $^1\!/_2$-inch measurement microphone was used as a continuous monitor of the sound field during testing. This microphone was also suspended by its cable from the ceiling and similarly oriented "upside down" (the purpose of this second microphone is described in the Instrumentation section below).

Two noise dosimeter microphones (No. 056-963; Quest Technologies, Oconomowoc, Wis.) were used for the "standard" personal noise exposure measurement positions, enabling both left and right top-of-shoulder measurements to be obtained simultaneously.

The "nonstandard" microphone positions were selected according to potential wearing positions specified by doseBusters USA for the ESP device. Two different versions of the ESP exist—an in-the-ear (earplug) and an over-the-ear (earmuff) system—both of which use a miniature electret condenser microphone cartridge (No. WM-60AY; Panasonic, Secaucus, N.J.). For the in-the-ear device, a small threaded earpiece encapsulates the microphone and serves as a holder for an insert-type eartip. Sound reaches the microphone through the hollow core of the threaded earpiece and certain styles of compatible eartips. Similar eartips are used in clinical audiometric testing as a combination sound delivery device and ambient noise attenuator when used with insert earphones. In the ESP application, the eartips provide hearing protection when the ESP earpiece is adequately inserted into the ear canal. In the earmuff version, the microphones are mounted inside the hard plastic shell of a typical noise-attenuating earmuff.

Measurements reported in this article were obtained with the ESP microphones located in three possible "secondary" positions where the intent is to measure a worker's unprotected noise exposure. Three pairs (a total of six) of ESP microphones were used, representing simultaneous left and right measurements of (1) the ESP microphones/earplugs draped around a subject's neck (resting on the person's chest), (2) the ESP microphones/earplugs hanging from a hard hat (near the wearer's ears), and (3) hard hat-mounted ESP earmuffs with the muffs rotated up and away from the subject's ears. Figure 1 shows all microphone locations.

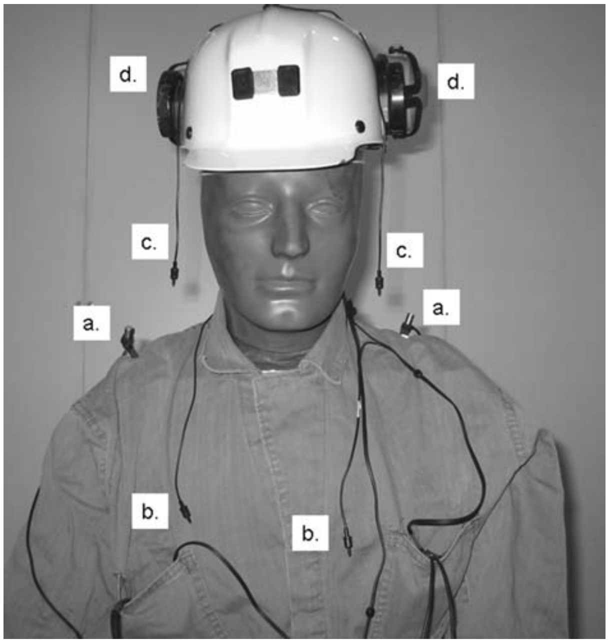


FIGURE 1. Placement of test microphones as worn on the body. (a) Quest Technologies dosimeter microphones at conventional shoulder position. (b) ESP devices resting on subject's chest—threaded earpiece microphone holders only—no noise-attenuating eartips attached. (c) ESP threaded earpiece microphone holders dangling or hanging from hard hat, without noise-attenuating eartips. (d) Identical ESP threaded earpieces mounted inside the shells of earmuffs (not visible in photo)

Instrumentation

An audio editing software program (Adobe Audition 1.0; Adobe Systems Inc.) was used to generate pink noise, as well as representative "surface," "drill," and "underground" noises; the last three noises are of the same spectrum types used in previous work done by MSHA.(4) Test signals were saved as WAV files (Windows PCM, 44,100 Hz sampling rate, 16-bit quantization, monaural) and played back through a computer sound card (Aardvark Direct Pro 24/96; Aardvark Computer Systems). For the diffuse field measurements, the output of the sound card was connected to a splitter/mixer (Rane SM26B; Mukilteo, Wash.) and routed to three loudspeakers (Electro Voice T251+; Burnsville, Minn.) in the reverberant enclosure (hearing protector test room).

Each loudspeaker was oriented in a different plane for maximum sound dispersion throughout the enclosure. Separate channels of a 1500-watt power amplifier (Sherbourn; North Billerica, Mass.) were used to drive each of the three loudspeakers. In the anechoic test chamber, the four test signals were routed from the output of the computer sound card to the external input on a Bruel & Kjaer Type 4224 Sound Source. The sound source was placed on a stand and vertically positioned to be level with the center-of-head location.

To avoid subjecting the human participants to very high noise levels, each noise signal was adjusted to produce an overall level of 90 dB SPL at the center-of-head position when

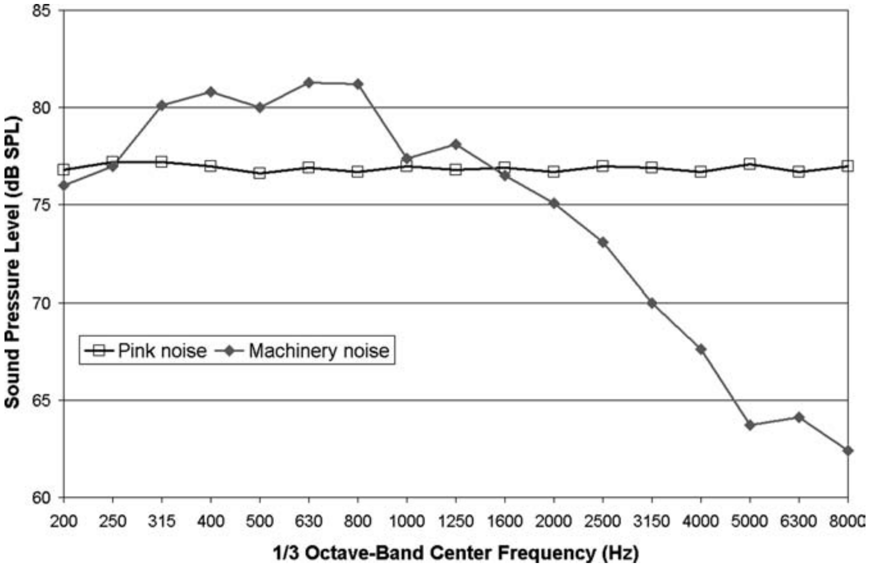


FIGURE 2. Measurements of the test signals at the center-of-head location (no subject or experimenter present). The same spectrums were used for both the diffuse and direct sound fields

played back in both of the test environments. When these adjustments are made, the pink and drill noise spectra are quite similar, and the surface and underground spectra closely approximate each other. Therefore, only the spectra for the pink noise and the underground noise (hereafter referred to as "machinery noise") are used in this report. Representative measurement results of the test signals at the center-of-head location (no subject or experimenter present) for both sound fields are shown in Figure 2.

Instead of using the actual dosimeter units for data acquisition, each of the test microphones was connected directly to a multichannel analyzer (LMS Pimento; LMS International; Leuven, Belgium) via an independent battery-operated power supply. The analyzer was controlled by a laptop computer, and was configured to measure 1/3-octave bands using a 15-sec average time for each measurement. A separate $\frac{1}{2}$-inch microphone (Bruel & Kjaer Type 4189) was positioned a few feet up and away from the center-of-head location and was used to continuously monitor the sound fields to ensure that the noise generation system remained stable. A picture of the laptop computer screen while collecting data is shown in Figure 3.

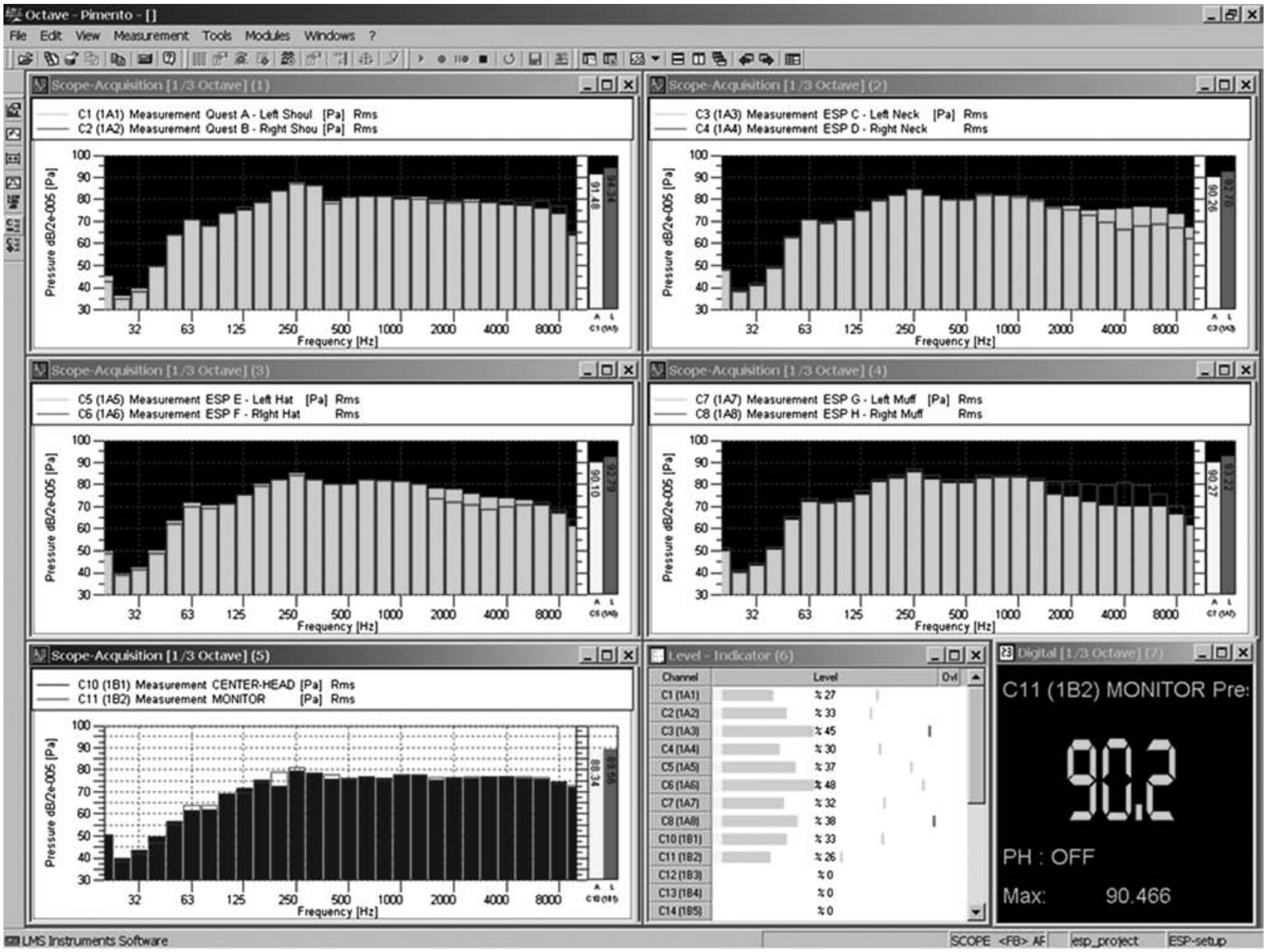
Data from each left/right pair of test microphones are contained in the top four windows, and readings from the center-of-head and monitor microphones are displayed in the lower left corner window. The overall level at the monitor microphone is also presented as a digital display in the lower right corner to allow the operator to quickly identify any signal generation problems during a test. The same instrumentation set-up was used for all data collection, regardless of whether a subject was being tested or center-of-head (i.e., subject absent) measurements were being conducted. Therefore, data from the center-of-head microphone channel was meaningless (and therefore discarded) while a subject was being tested, and data from all dosimeter microphone channels were not relevant when the center-of-head measurements were taken.

Procedures

A calibration check with a sound level calibrator (Type 4231; Bruel & Kjaer) was performed on all 10 microphones before each test session. The manufacturer's standard adapter (No. 56-989) was used to accommodate the Quest microphones, and a small machined aluminum adaptor was designed specifically to fit the ESP earpieces (microphone holders).

A Quest microphone was mounted vertically on the midpoint of each subject's shoulder, with the grid pointing upward. To replicate the three possible secondary wearing positions, the ESP microphones were positioned as follows: (1) the wiring harness for an earplug-type set of microphones was draped around the back of the subject's neck, with the microphones/earplugs positioned to rest evenly across the chest; (2) a second set of earplug-type microphones were affixed to the hard hat, and positioned to hang down on each side approximately 2 inches above the shoulder; (3) hard hat-mounted earmuffs with integral microphones were rotated up and back so that the cushions did not touch the hard hat. For the earplug versions, the chest level ESP microphones were fitted with expandable polyvinyl foam inserts; preformed four-flange earplugs were attached to the earpieces suspended from the hard hat. These eartips (earplugs) were chosen as representative devices that would typically be attached to the microphone holders when an ESP system is being used.

In the reverberant room (diffuse field), the subjects were seated on a small stool, with the head at the room's center. In turn, each of the four test signals was played while a measurement was taken with the multichannel analyzer. Initially, the first few subjects were rotated horizontally with the same four measurements repeated at 45°



Channel	Level	Ovl
C1 (1A1)	% 27	
C2 (1A2)	% 33	
C3 (1A3)	% 45	
C4 (1A4)	% 30	
C5 (1A5)	% 37	
C6 (1A6)	% 48	
C7 (1A7)	% 32	
C8 (1A8)	% 38	
C10 (1B1)	% 33	
C11 (1B2)	% 26	
C12 (1B3)	% 0	
C13 (1B4)	% 0	
C14 (1B5)	% 0	

C11 (1B2) MONITOR Pre:

90.2

PH : OFF

Max: 90.466

FIGURE 3. Screenshot of laptop computer screen while collecting soundfield data.

increments; however, no significant spatial variability in the diffuse sound field was found, and the rotation scheme was discontinued.

Subjects were seated on the same swivel stool during testing in the anechoic chamber. Measurements were taken at eight different azimuthal angles (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°, and repeated at 360°), as the subject was rotated clockwise in a horizontal circle as viewed from above. The 0° position and the duplicate measurement at 360° were defined as directly facing the sound source. The sound source remained stationary throughout all testing, with the center of the loudspeaker cone at the same height as the subject's center-of-head location.

Finally, a set of measurements were taken to compare the frequency response of each test microphone with the precision measurement microphone. These measurements were taken at the center-of-head location in the reverberant test chamber, with the subject absent. This comparison is important, since the initial hearing loss damage risk criteria was based primarily on an assessment of workplace noise levels as measured in a diffuse field at the worker's center-of-head location but with the worker absent.

RESULTS

Measurement errors for each left/right pair of test microphones are shown in Figure 4. These graphs were generated by subtracting the precision microphone reading from the individual test microphone reading when each of the microphones was placed (one at a time) at the center-of-head position in the diffuse sound field (no subject or experimenter was present). The Quest dosimeter microphones deviated slightly from the "true" center-of-head levels, mostly in the high frequencies (Figure 4a). A resonant peak centered around 4000 Hz was observed with the ESP earplug-type microphones (Figure 4b,c). The muff-mounted ESP microphones differed the most from the precision microphone reading (Figure 4d).

Tables I and II contain the mean A-weighted errors and standard deviations measured with the various test microphones worn by the human subjects, as compared with the precision $\frac{1}{2}$-inch measurement microphone undisturbed center-of-head readings. Negative values indicate that the test microphone produced a lower reading than the precision reference microphone, while positive values indicate an erroneously high reading

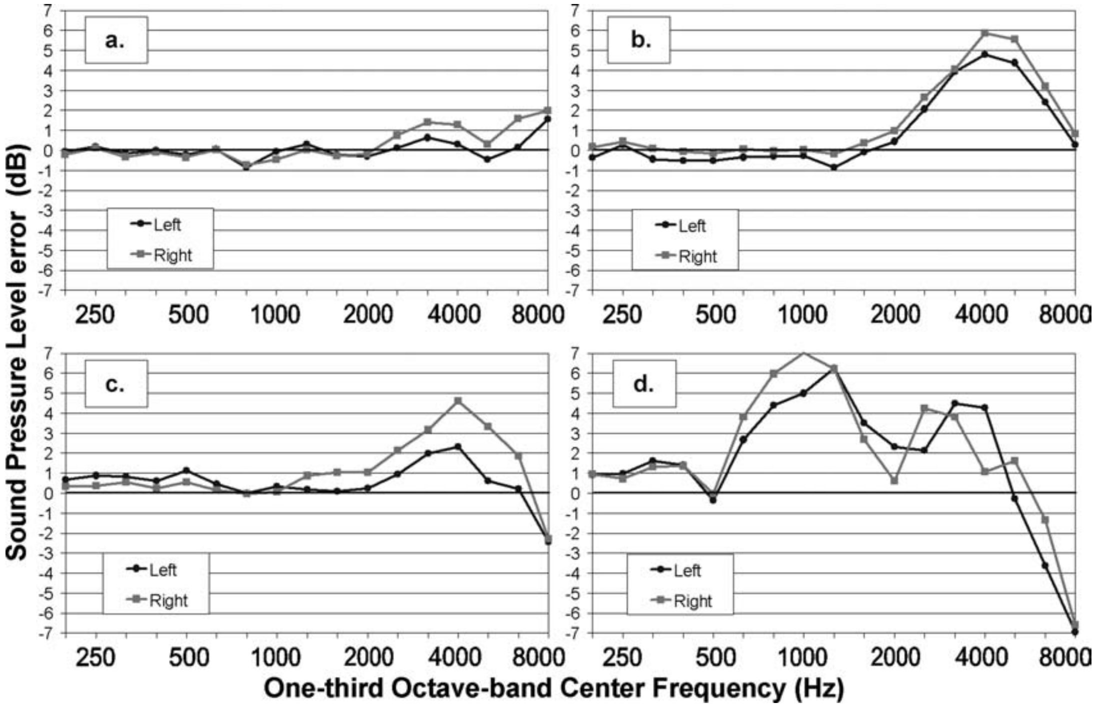


FIGURE 4. Individual test microphone errors (test microphone reading minus the precision microphone reading at the center-of-head position in the diffuse sound field with no subject or experimenter present). (a) Quest dosimeter microphones. (b) ESP microphones contained inside threaded plastic earpiece, with foam eartip attached. (c) ESP microphones contained inside threaded plastic earpiece, with four-flanged eartip attached. (d) ESP microphones contained inside threaded plastic earpiece and mounted inside earmuffs attached to a hard hat

from the test microphone. These results reflect the individual microphone frequency response errors, the diffraction and resonance/antiresonance effects of the microphone mounting and supporting structures, and the body-worn microphone placement effects. Figures 5 through 13 graphically display the results in which box plots are used to give a better visualization of the data distribution. The lower boundary of each box represents the 25th percentile, and the upper boundary represents the 75th percentile. The vertical length of the box represents the interquartile range, which means that 50% of all data points are within the box. The horizontal line inside the box indicates the median value. Vertical lines (whiskers) are drawn from the edges of the box to encompass the 95th percentile (upper line) and the 5th percentile (lower line).

Figure 5 shows that in the diffuse field, the shoulder-mounted dosimeter microphones tended to slightly underreport the actual noise level. Larger measurement errors occurred with the pink noise spectrum, which contained more high-frequency energy than the machinery noise spectrum. The ESP microphones dangling from the hardhat produced similar results. The ESP microphones draped around the neck and resting

TABLE I. Mean A-Weighted Errors and Standard Deviations—Pink Noise Spectrum

	Shoulder-Left		Shoulder-Right		Left-Chest		Right-Chest		Hanging-Left		Hanging-Right		Muff-Left		Muff-Right	
	Error	SD	Error	SD	Error	SD	Error	SD	Error	SD	Error	SD	Error	SD	Error	SD
Diffuse	−1.0	0.4	−0.7	0.3	1.2	0.4	1.1	0.9	−1.0	1.0	−0.5	0.8	2.1	0.3	2.7	0.4
0°	0.3	0.5	0.3	1.1	3.4	0.8	4.0	0.9	2.2	0.8	2.9	0.5	−3.6	0.4	−3.9	0.7
45°	1.3	0.4	−5.2	1.2	3.8	0.8	2.3	1.7	3.4	0.8	0.0	1.3	−0.8	1.4	−0.7	0.8
90°	2.5	0.3	−5.5	0.9	1.5	0.9	−2.3	1.0	3.8	0.6	−4.2	0.6	4.1	0.9	2.1	1.0
135°	2.4	0.4	0.0	0.9	−3.7	0.8	−6.9	1.4	2.6	0.8	−5.7	1.0	6.5	0.8	5.3	0.6
180°	1.1	0.5	2.1	0.4	−7.0	0.8	−7.6	1.0	−0.1	1.1	−0.1	2.0	5.5	0.7	6.3	0.6
225°	−2.2	1.3	3.1	0.4	−6.9	0.8	−3.4	0.9	−6.0	0.7	3.3	1.5	5.3	0.7	5.5	0.6
270°	−6.4	0.6	2.4	0.3	−1.8	0.9	2.1	0.8	−4.7	0.5	4.2	0.9	3.1	0.6	4.6	0.7
315°	−4.5	1.4	1.6	0.5	2.1	1.2	3.9	1.0	−1.6	1.2	4.0	0.8	0.0	0.8	−0.2	0.9

TABLE II. Mean A-Weighted Errors and Standard Deviations—Machinery Noise Spectrum

	Shoulder-Left		Shoulder-Right		Left-Chest		Right-Chest		Hanging-Left		Hanging-Right		Muff-Left		Muff-Right	
	Error	SD	Error	SD	Error	SD	Error	SD	Error	SD	Error	SD	Error	SD	Error	SD
Diffuse	−0.2	0.4	−0.2	0.4	1.1	0.6	1.0	0.5	−0.1	1.2	−0.1	0.7	3.1	0.5	4.1	0.4
0°	0.8	0.7	0.1	1.3	4.5	0.9	3.8	0.6	2.8	0.8	2.8	0.6	−1.2	0.5	−1.3	0.7
45°	2.3	0.4	−3.6	0.9	4.8	0.7	2.3	1.5	4.8	0.9	0.0	1.1	0.8	1.4	1.4	0.7
90°	3.3	0.3	−4.3	0.4	2.5	1.0	−1.3	1.0	5.2	0.7	−3.0	0.4	5.5	0.8	2.8	0.8
135°	3.2	0.4	0.5	0.9	−1.6	0.6	−5.4	1.2	4.0	1.0	−4.4	0.7	7.2	0.5	5.2	0.9
180°	2.1	0.7	3.0	0.5	−5.4	0.8	−6.2	0.8	0.4	1.4	−0.6	2.0	6.4	0.5	6.8	0.5
225°	−1.7	1.2	3.5	0.4	−4.9	1.0	−1.9	0.6	−4.5	0.5	3.6	1.2	5.5	0.7	6.9	0.5
270°	−4.4	0.4	3.2	0.4	−0.4	0.7	2.2	0.6	−2.7	0.4	4.8	0.9	3.4	0.6	6.1	0.5
315°	−3.5	1.1	2.3	0.6	3.4	0.8	3.8	0.4	−0.7	0.9	4.4	0.7	1.5	0.8	1.9	0.8

on the subject's chest averaged about 1 dB(A) high, and the earmuff-mounted ESP microphone readings were consistently 2–4 dB(A) high. The largest ESP earmuff measurement errors occurred with the machinery noise spectrum, where there was predominantly low-frequency energy.

Figure 6 displays the direct field results with the subject directly facing the sound source (0° azimuth). The shoulder-mounted microphones read less than 1 dB(A) high, while the earplug-type ESP microphones were approximately 2–4 dB(A) high. Readings from the muff-mounted ESP microphones were approximately 1–4 dB(A) low.

Figures 6–13 reveal distinct differences in the microphone errors depending on the angle of the incident sound. The range of average errors for the shoulder-mounted microphones was −6.4 dB(A) [pink noise, 270°] to +3.5 dB(A) [machinery noise, 225°]; average errors for the microphones resting on the subject's chest ranged from −7.6 dB(A) [pink noise, 180°] to +4.8 dB(A) [machinery noise, 45°]; average errors for

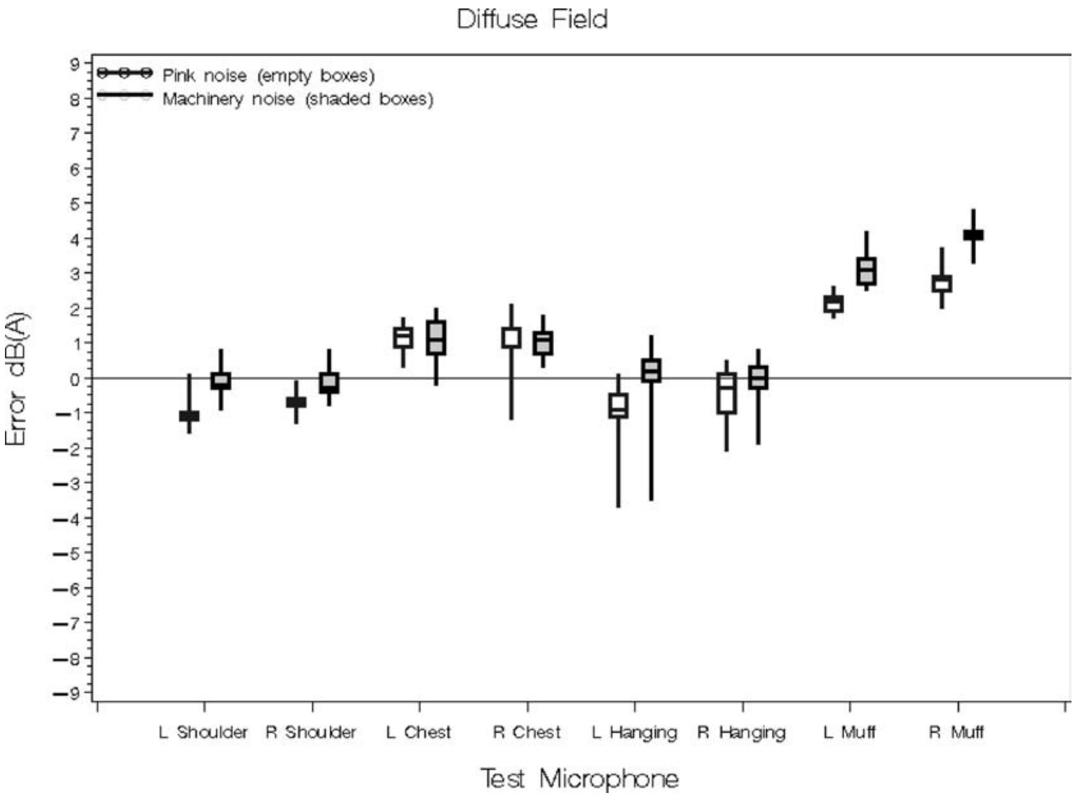


FIGURE 5. Results obtained for the test microphones in the diffuse sound field. Overall A-weighted errors are shown for each test microphone while measuring pink and machinery noise spectrums, as compared with the precision microphone center-of-head measurement

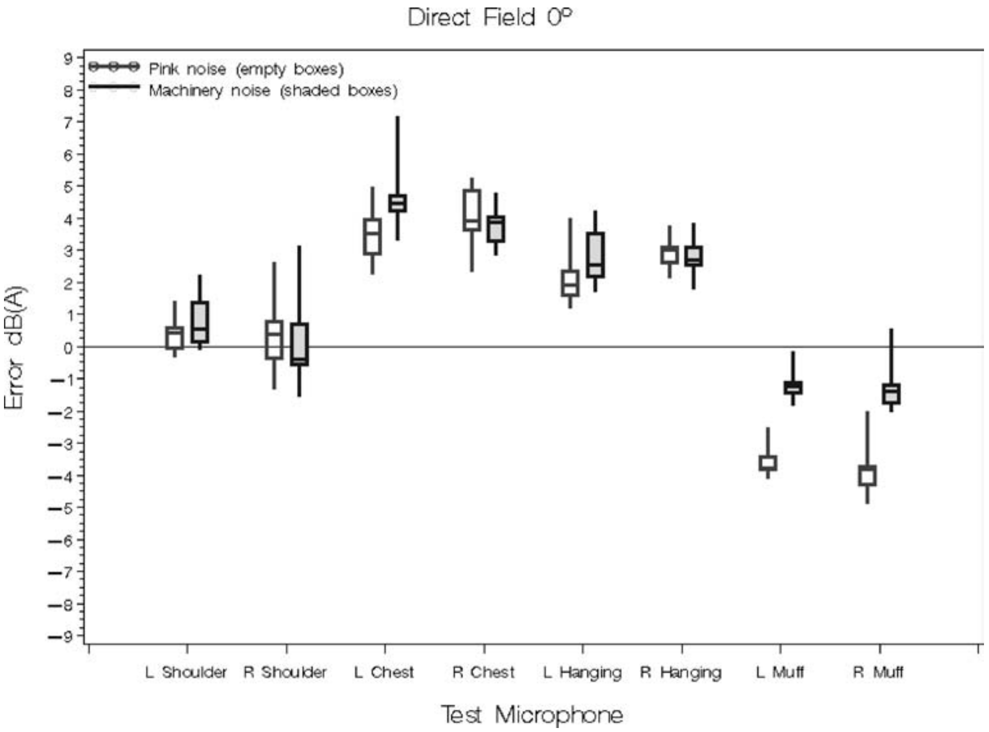


FIGURE 6. Results obtained for the test microphones in the direct sound field at 0°. Overall A-weighted errors are shown for each test microphone while measuring pink and machinery noise spectrums, as compared with the precision microphone center-of-head measurement

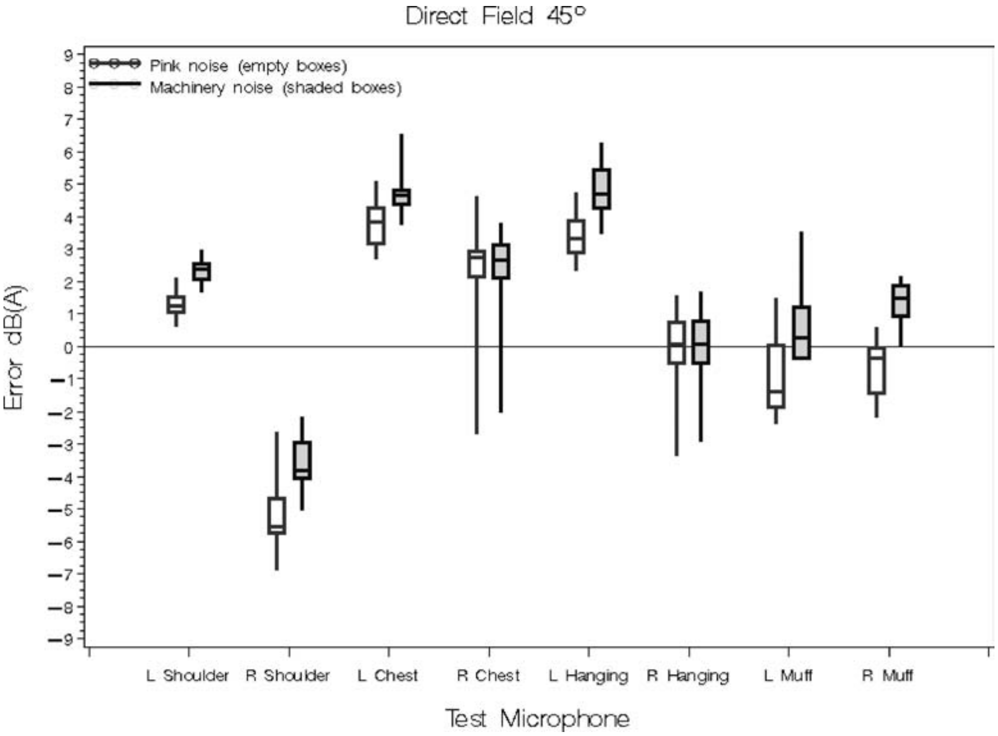


FIGURE 7. Results obtained for the test microphones in the direct sound field at 45°. Overall A-weighted errors are shown for each test microphone while measuring pink and machinery noise spectrums, as compared with the precision microphone center-of-head measurement

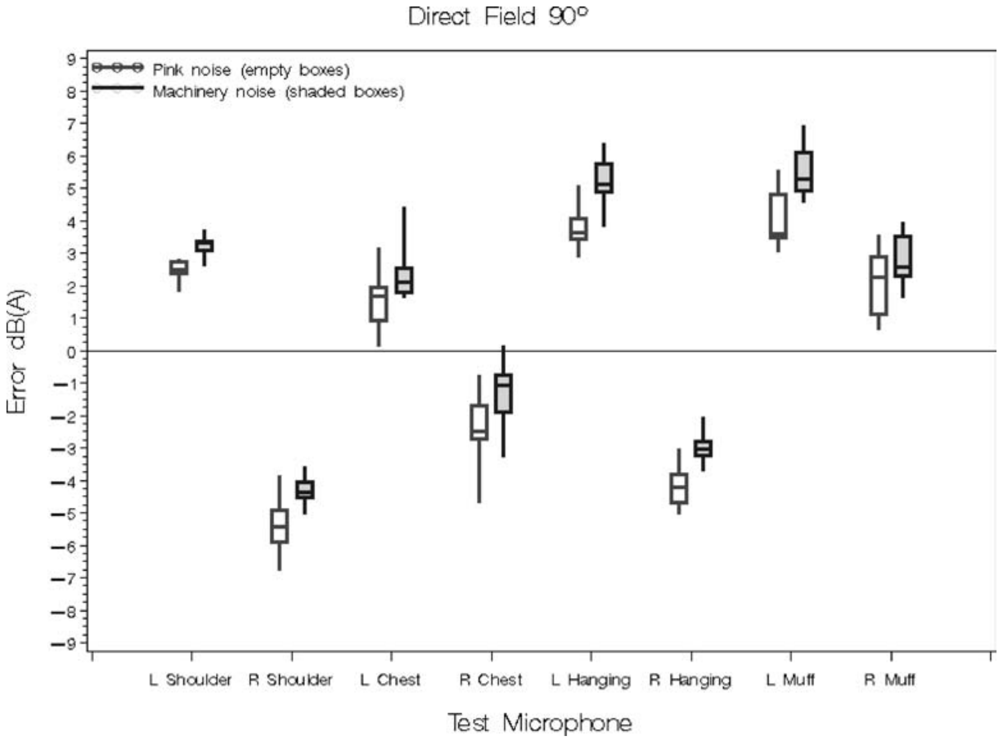


FIGURE 8. Results obtained for the test microphones in the direct sound field at 90°. Overall A-weighted errors are shown for each test microphone while measuring pink and machinery noise spectrums, as compared with the precision microphone center-of-head measurement

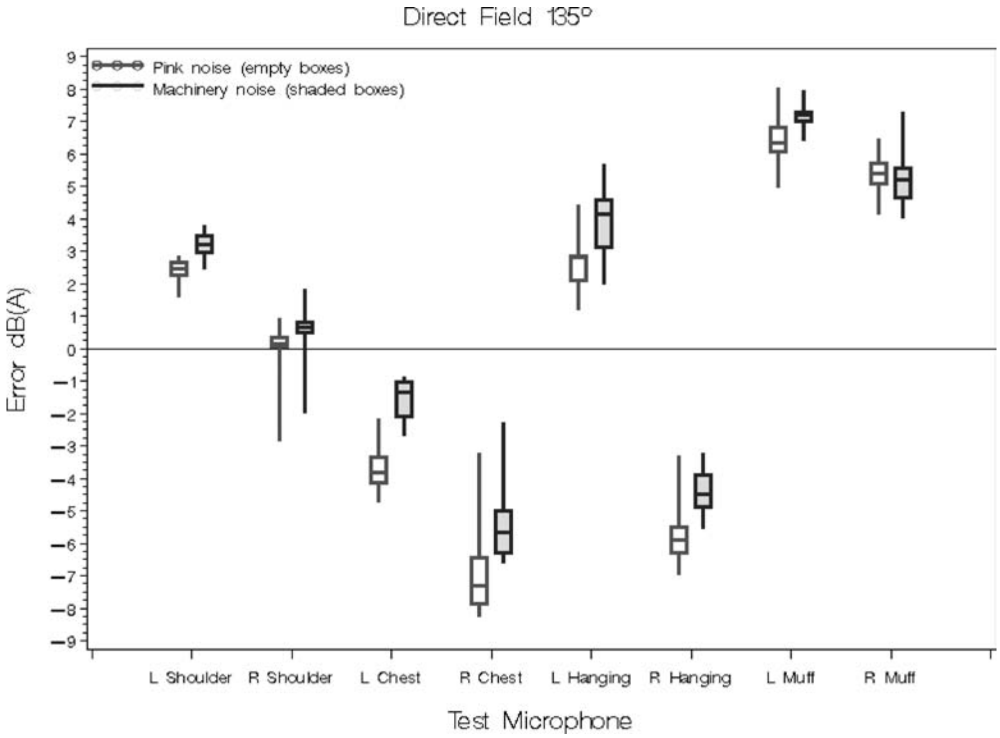


FIGURE 9. Results obtained for the test microphones in the direct sound field at 135°. Overall A-weighted errors are shown for each test microphone while measuring pink and machinery noise spectrums, as compared with the precision microphone center-of-head measurement

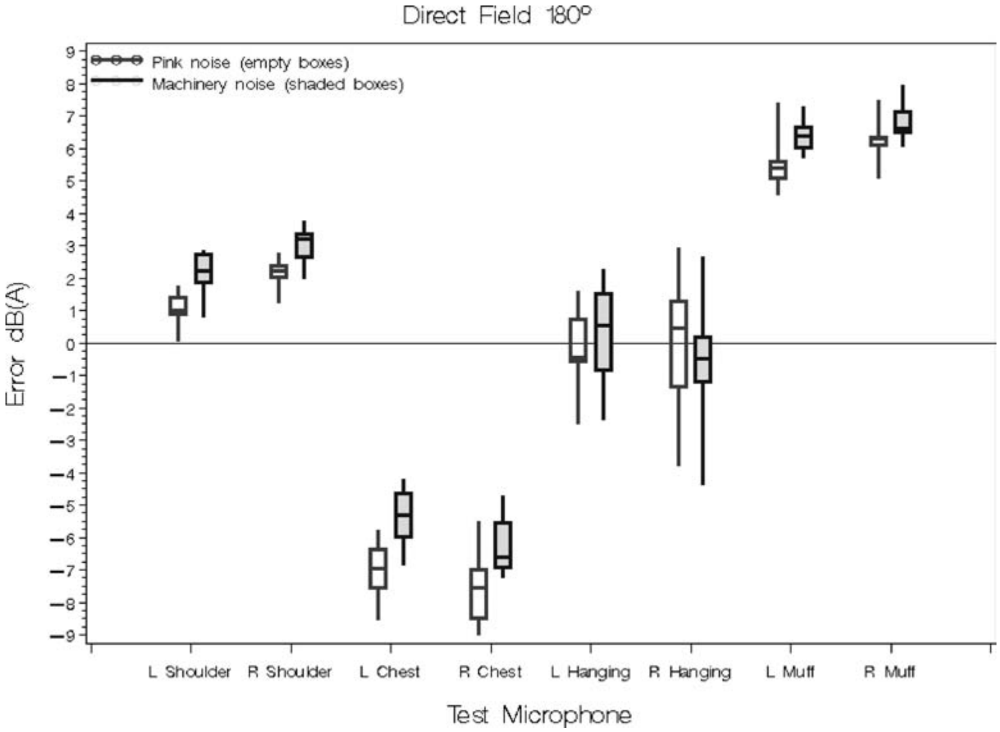


FIGURE 10. Results obtained for the test microphones in the direct sound field at 180°. Overall A-weighted errors are shown for each test microphone while measuring pink and machinery noise spectrums, as compared with the precision microphone center-of-head measurement

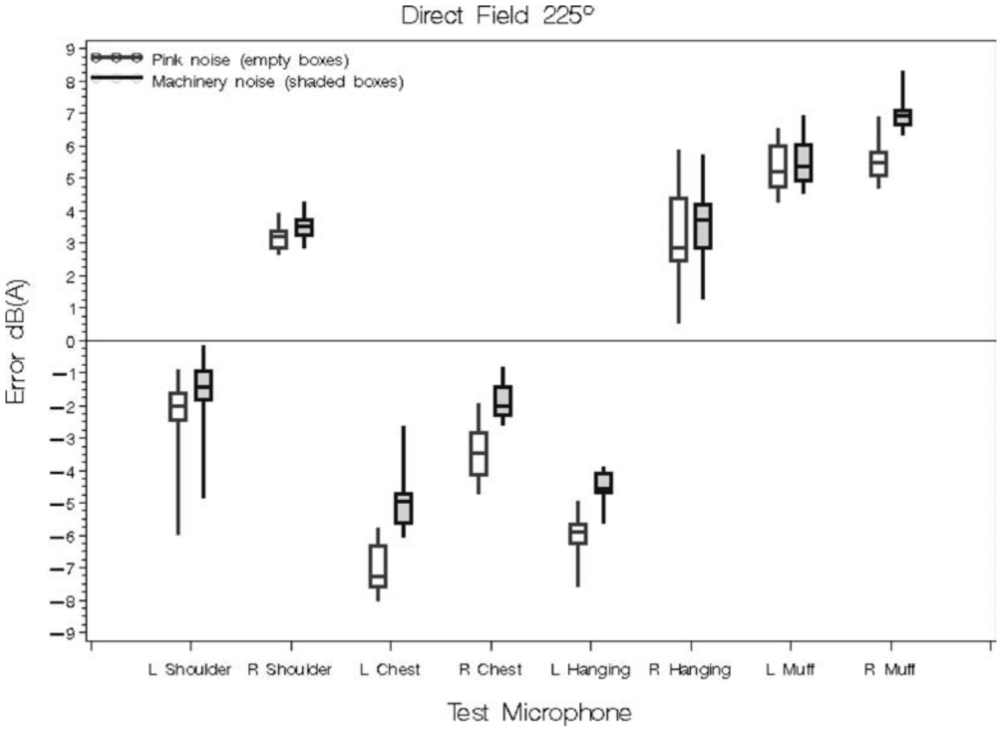


FIGURE 11. Results obtained for the test microphones in the direct sound field at 225°. Overall A-weighted errors are shown for each test microphone while measuring pink and machinery noise spectrums, as compared with the precision microphone center-of-head measurement

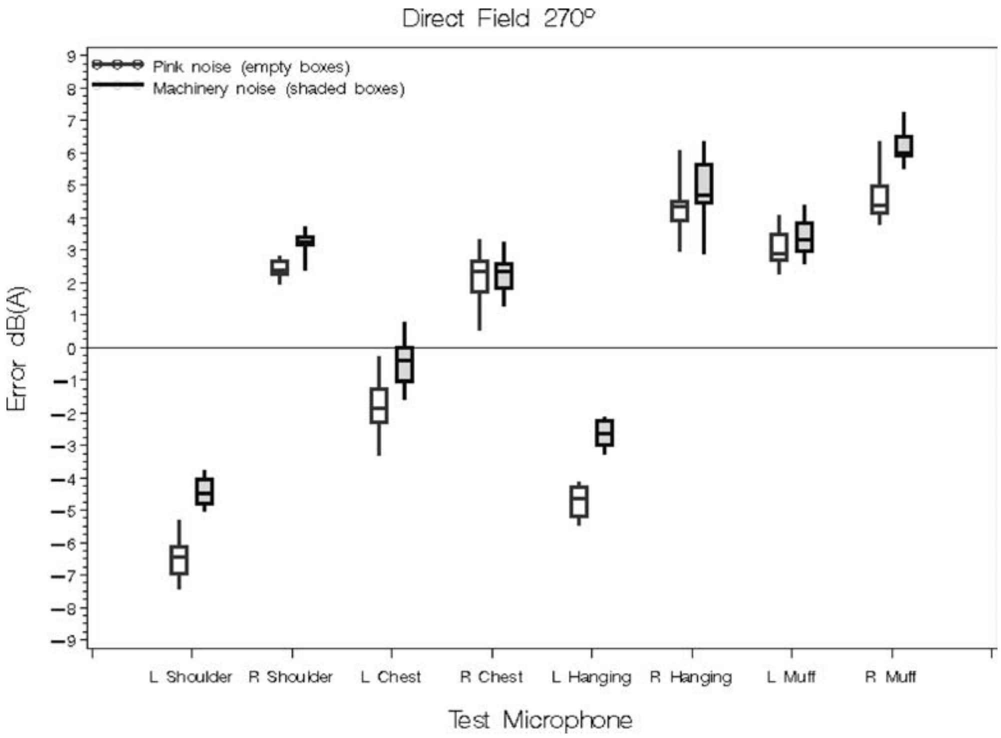


FIGURE 12. Results obtained for the test microphones in the direct sound field at 270°. Overall A-weighted errors are shown for each test microphone while measuring pink and machinery noise spectrums, as compared with the precision microphone center-of-head measurement

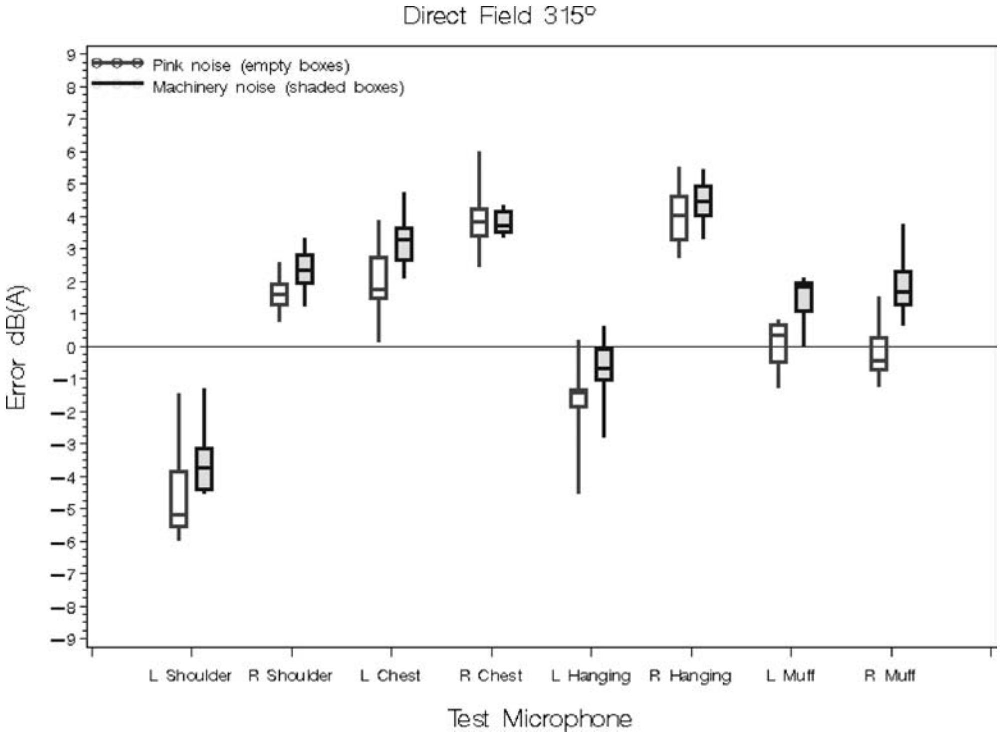


FIGURE 13. Results obtained for the test microphones in the direct sound field at 315°. Overall A-weighted errors are shown for each test microphone while measuring pink and machinery noise spectrums, as compared with the precision microphone center-of-head measurement

the hanging (from hard hat) microphones ranged from −6.0 dB(A) [pink noise, 225°] to +5.2 dB(A) [machinery noise, 90°]; and average errors for the muff-mounted microphones ranged from −3.9 dB(A) [pink noise, 0°] to +7.2 dB(A) [machinery noise, 135°].

DISCUSSION

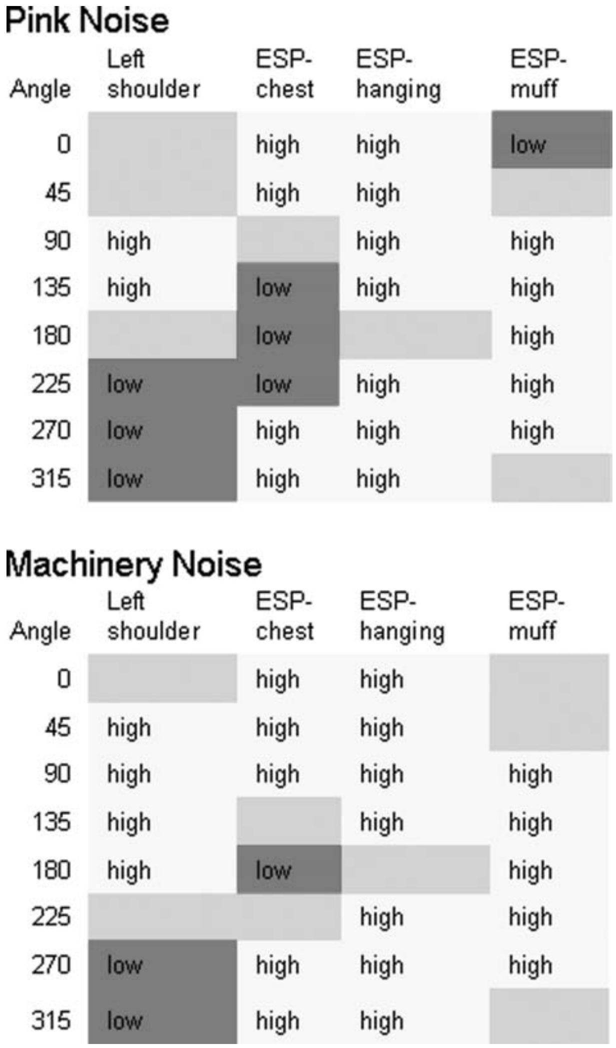
The frequency response of the Quest Technologies dosimeter microphones deviated only slightly from the precision 1/2-inch measurement microphone used in this study. Hollow-core eartips (the polyvinyl foam or four-flanged inserts) attached to the ESP microphones caused a resonant peak in the frequency response centered around 4000 Hz. The muff-mounted ESP microphones differed the most from the precision microphone reading due to fact that the microphone was mounted inside the earmuff.

As seen in Figures 6–13, the results for certain pairs of direct field measurements (0° and 180°; 45° and 315°; 90° and 270°; 135° and 225°) exhibit opposite trends due to the symmetry of measurements. As expected, the magnitude of the errors varied depending on the angle of incidence and type of noise (i.e., low-frequency vs. high-frequency content). This stands to reason when the position of the sound source and the rotation scheme are considered.

As a validity check for these data, the left-shoulder results were compared with those published by Giardino and Seiler[(4)] in 1996. The diffuse field errors and the direct field errors from 0° through 180° were generally within 1 dB of the results obtained in the present study. Although the error patterns were similar, somewhat larger errors (absolute values of 1–2 dB greater) were observed in the present study than in the earlier MSHA data at the 225°, 270°, and 315° azimuths.

A method to minimize the errors associated with microphone placement is built into the ESP manufacturer's new noise exposure monitoring paradigm. One aspect of this new approach to noise monitoring is to always use both a left-side and a right-side microphone instead of a single left or right shoulder-mounted microphone. According to the manufacturer, the dose computation algorithm programmed into the ESP dosimeter unit incorporates the higher sound level received by either microphone at any given time. The intent is to limit the range of potential errors for the nonstandard measurement locations to "positive" values, which would provide a "conservative" estimate of a worker's actual noise exposure in a directional sound field. This means that the ESP dosimeter reading possibly could be higher than a traditional dosimeter measurement taken with a single shoulder-mounted microphone. A higher reading would be obtained by the ESP device since the sound level at both microphones is measured simultaneously, and the higher reading is used to calculate the dose.

Any number of plausible and/or typical work scenarios could be envisioned that either accentuate or minimize the effects of dosimeter microphone measurement errors. Assuming that the subject/worker spent an entire workshift facing exactly the same direction (i.e., both the sound source and the worker remained stationary) and using greater than 2 dB(A) as the criterion for high/low readings, the chart in Figure 14 summarizes the direct field results. It is important to note that these results are for only one shoulder-mounted microphone (i.e., left shoulder), since only one dosimeter is used traditionally to monitor a worker's dose. On the other hand, the ESP measurement paradigm calls for the higher of the two independent microphone readings to be used in the dose calculation. Therefore, the higher of the two microphone readings for each of the three secondary wearing positions was used in this analysis. Figure 14 highlights the possible high and low extremes that could be obtained.



Pink Noise

Angle	Left shoulder	ESP-chest	ESP-hanging	ESP-muff
0		high	high	low
45		high	high	
90	high		high	high
135	high	low	high	high
180		low		high
225	low	low	high	high
270	low	high	high	high
315	low	high	high	

Machinery Noise

Angle	Left shoulder	ESP-chest	ESP-hanging	ESP-muff
0		high	high	
45	high	high	high	
90	high	high	high	high
135	high		high	high
180	high	low		high
225			high	high
270	low	high	high	high
315	low	high	high	

FIGURE 14. Summary of direct field results indicating high (+2 dB) and low (–2 dB) differences between the true center-of-head level and the test microphone readings, assuming the worker and sound source are stationary. Left-shoulder reading represents a single measurement, while the higher of the left/right ESP readings was used

CONCLUSIONS

Measurements obtained from the eight different test microphones at various body-worn positions were compared with measurements from the $^1/_2$-inch precision measurement microphone at the center-of-head position (subject absent). This demonstrated the frequency-dependent errors due to a combination of both frequency-dependent sensitivity differences between the test and reference microphones themselves, as well as body placement and microphone supporting structure (including diffraction and cavity resonance/antiresonance) effects, as compared with center-of-head readings obtained with the subject absent. In a diffuse field, overall dB(A) errors due to dosimeter microphone placement were found to be minor for most of the test microphones/locations. Conversely, direct-field microphone placement effects were found to be quite large depending on the microphone position and supporting structure, sound source location, and noise spectrum.

Technological advancements such as the ESP dual-microphone monitoring methodology may be able to minimize some of the potential problems currently encountered when conducting personal noise dosimetry measurements with body-worn microphones. Additional research in this area might include investigating the use of signal processing techniques to offset the inherent frequency response errors and placement effects when inexpensive (i.e., nonprecision) body-worn microphones are used.

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